SOFIA Joint Impact Proposal:
A complete velocity resolved 3-D [CII] map of the M51 grand-design spiral galaxy:

Unraveling the impact of spiral density waves on the evolution of the ISM and star formation

Jorge L. Pineda (US PI), Jürgen Stutzki (DE PI), Paul Goldsmith, Christian Fischer, Maria Kapala, Jin Koda, Christof Buchbender, Bhaswati Moorkejea, Carsten Kramer, Monika Ziebart, Nick Scoville, Ralf Klessen, Rowan Smith, Simon Glover, Karin Sandstrom

The whirlpool galaxy (M51, NGC 5194).

- M51 is a grand-design spiral galaxy at 8.58 Mpc.
- Interacted with the companion galaxy NGC5195 about 400 Myr ago.
- A wide range of multi-wavelength images exist.
- SOFIA beam can separate the arms from the inter-arm regions, but cannot resolve the arms.
- High resolution spectroscopy can resolve them in velocity space.

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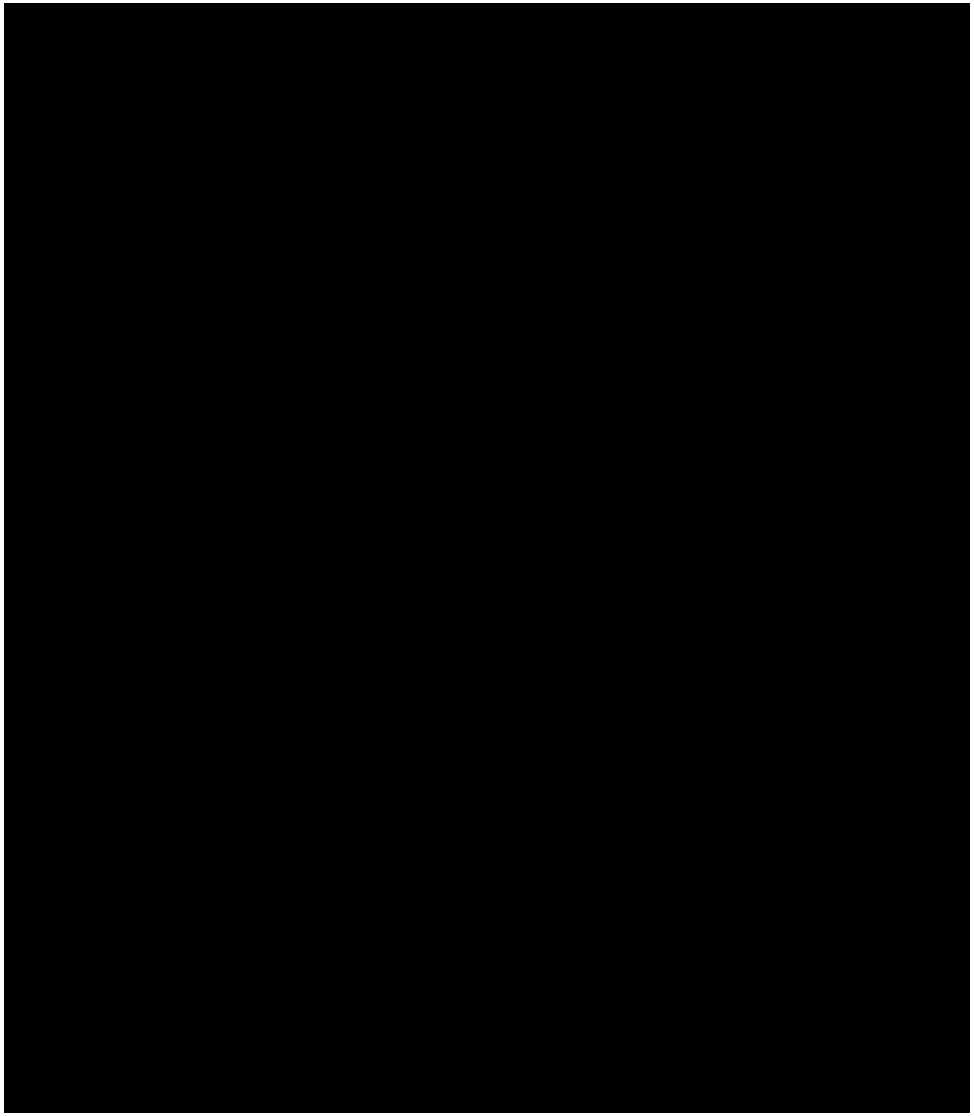
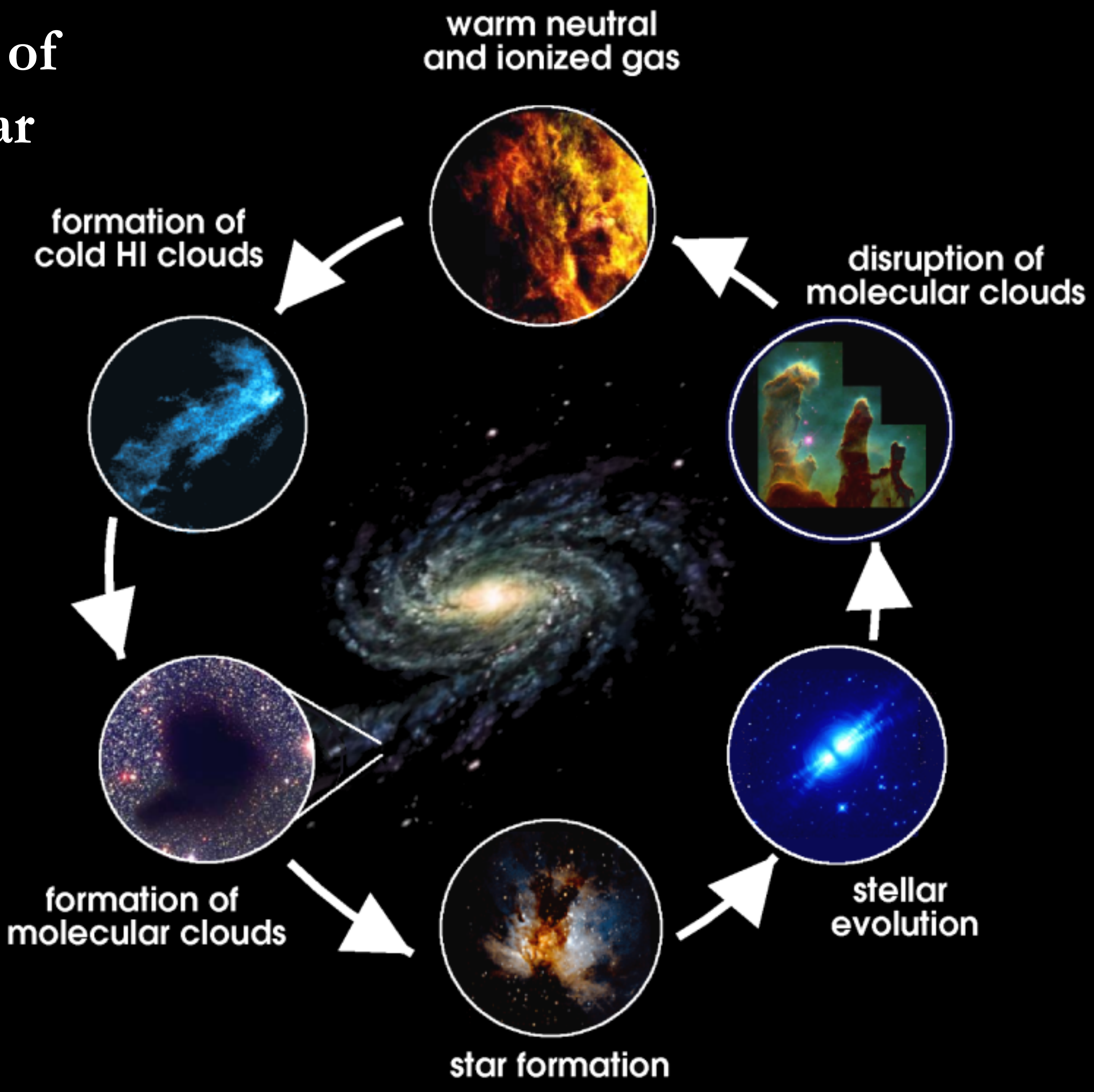


The lifecycle of the interstellar matter

Atomic Hydrogen Clouds (**H**)

Molecular Hydrogen Clouds ($\mathbf{H_2}$)

Ionized Medium ($\mathbf{H^+}$)



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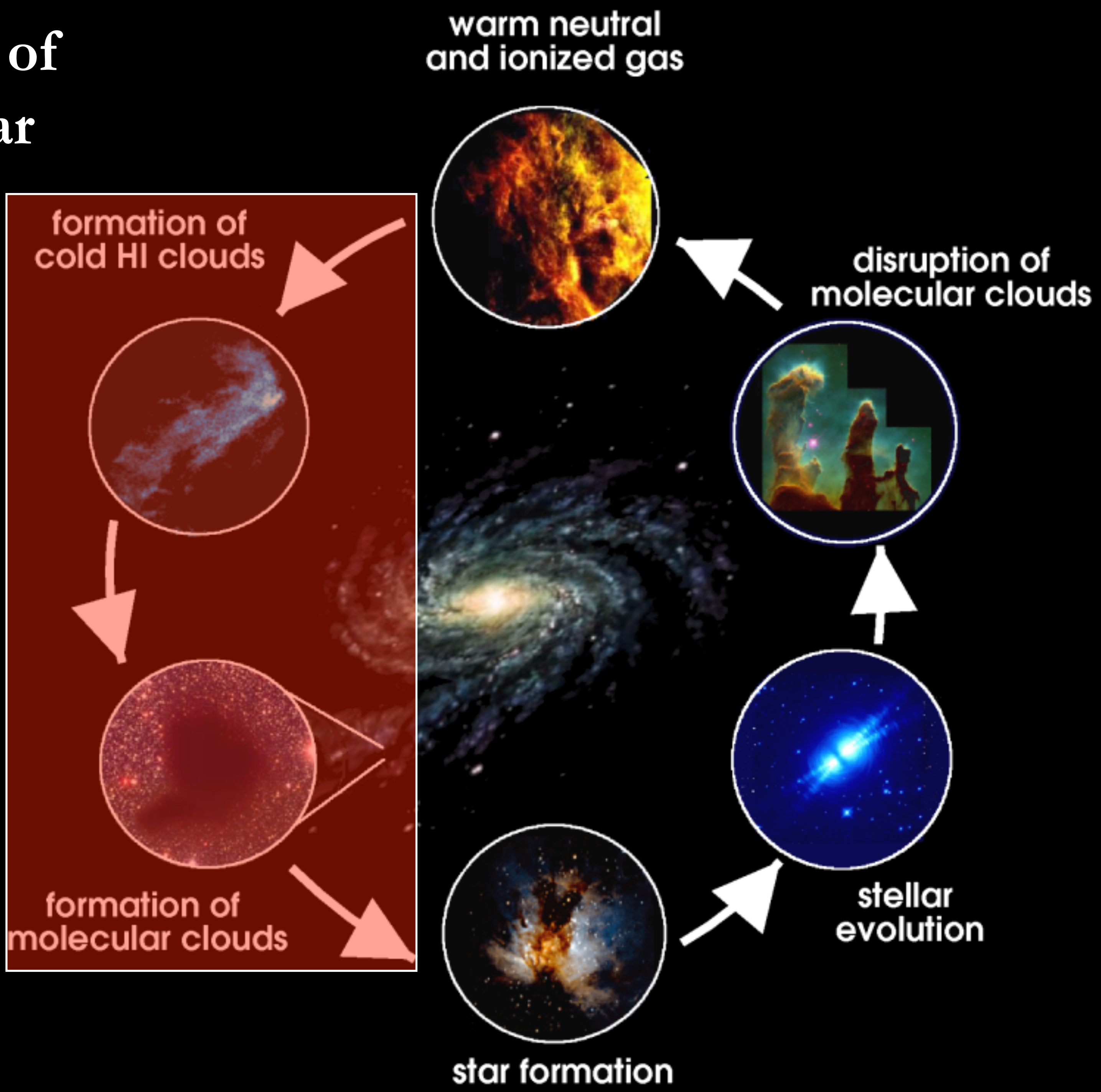


In spiral arms Giant Molecular clouds (where star formation takes place) can form the agglomeration of HI clouds (Classic Picture).

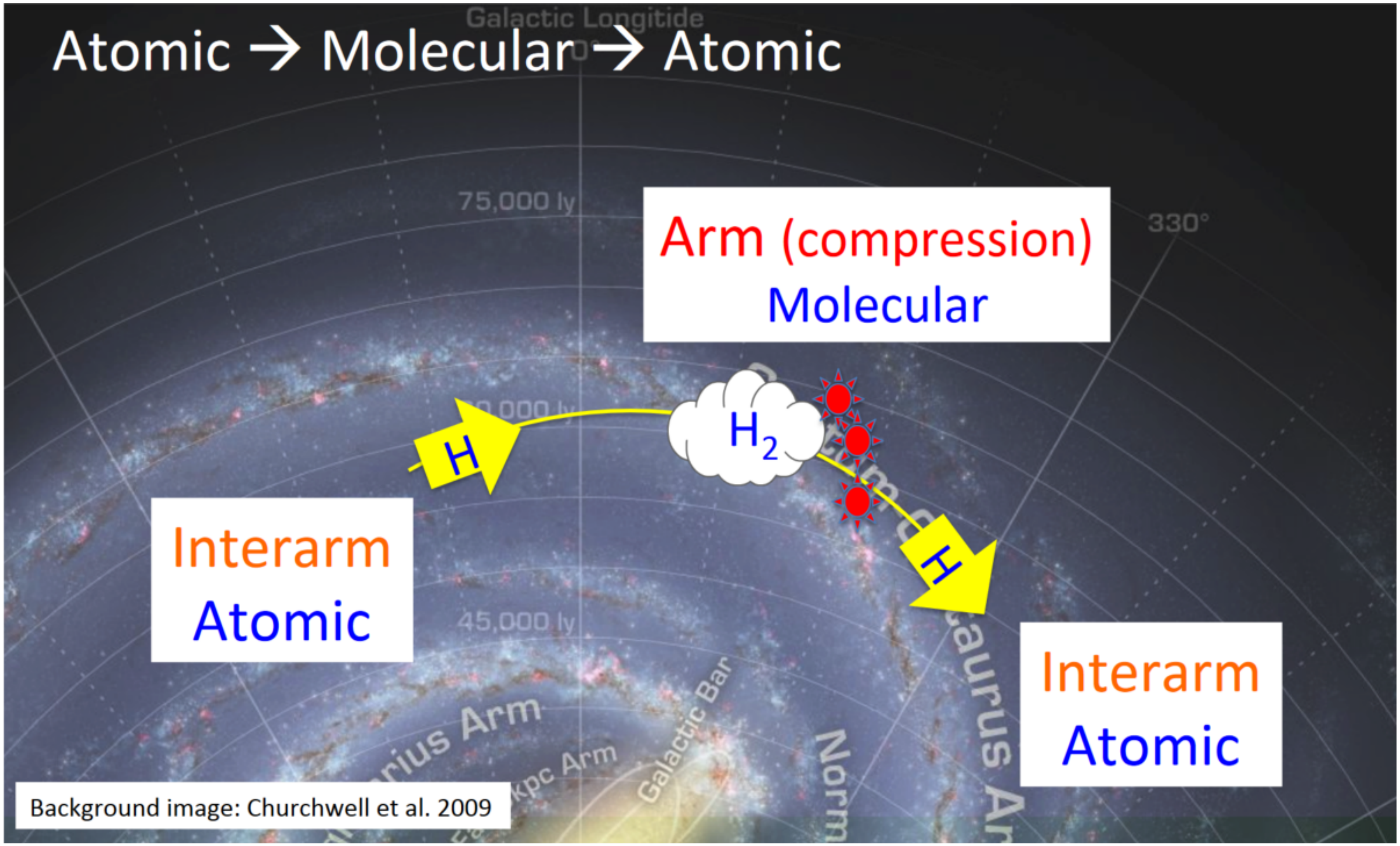
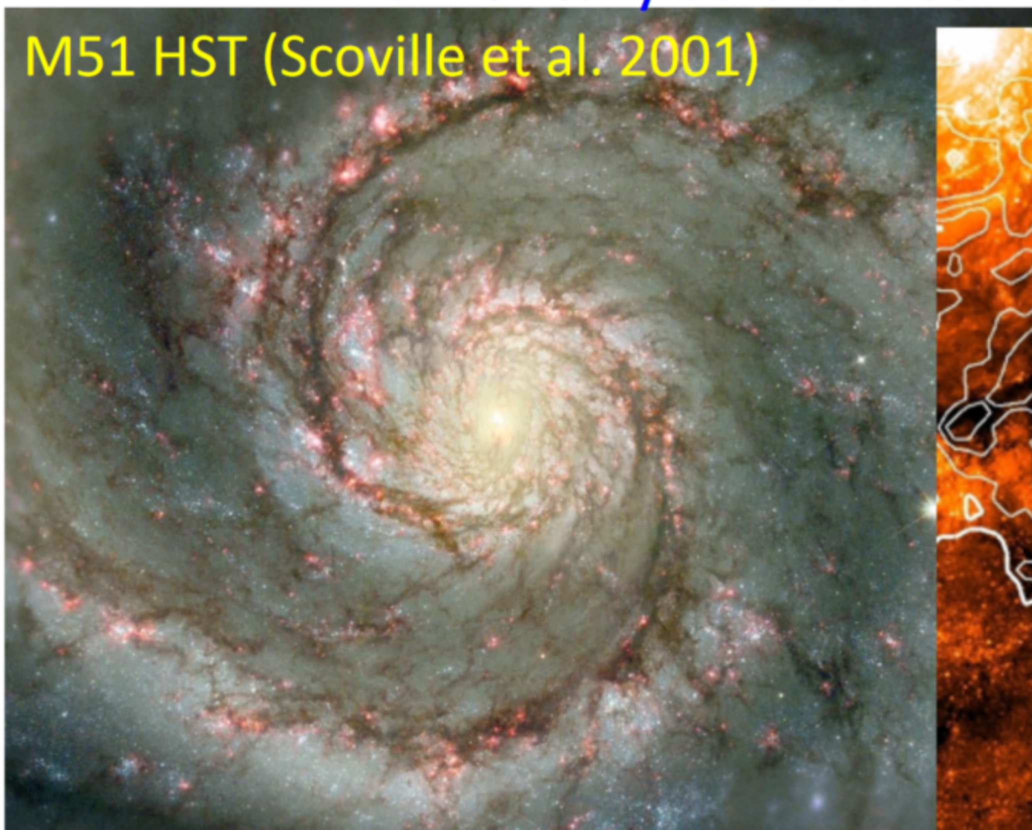
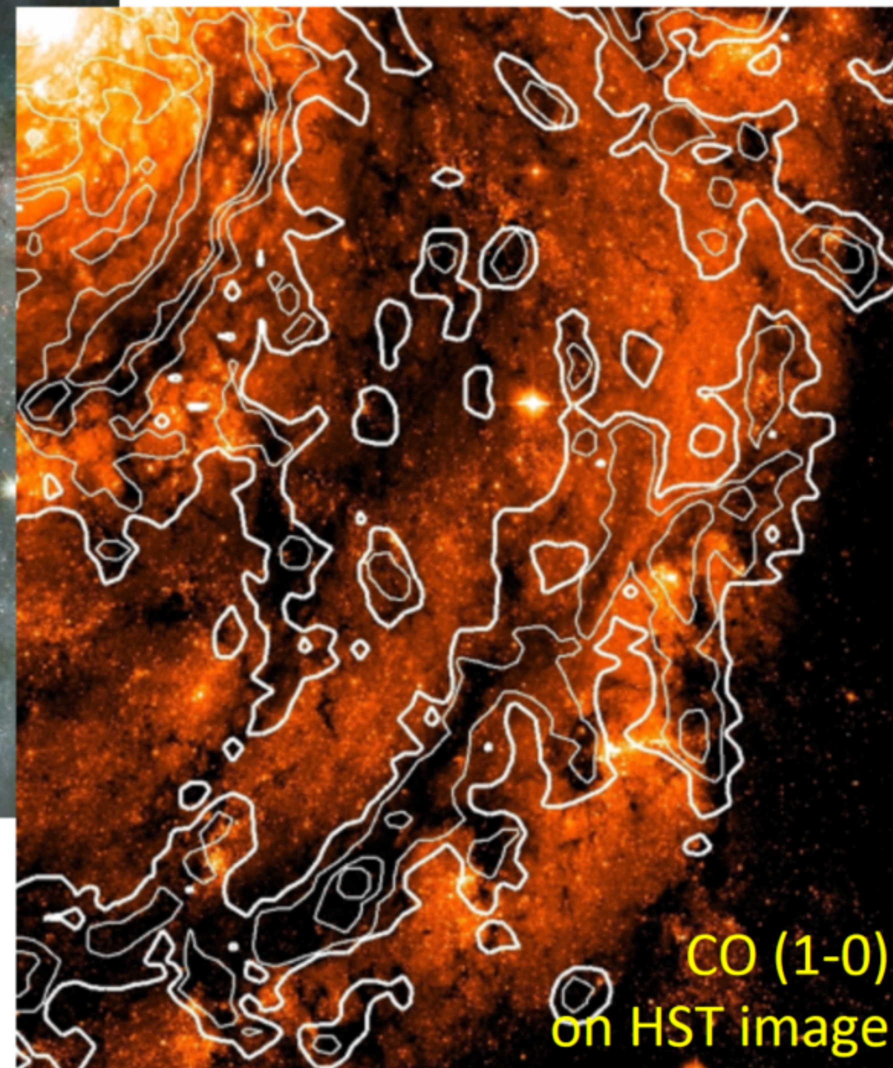


Image courtesy of Jin Koda

Spurs/Feathers in CO(1-0)

Filamentary structures in interarm regions





Spurs = chains of GMCs

Koda et al. 2009

Koda et al. 2009 proposes that molecular clouds are formed from the agglomeration of smaller molecular clouds.

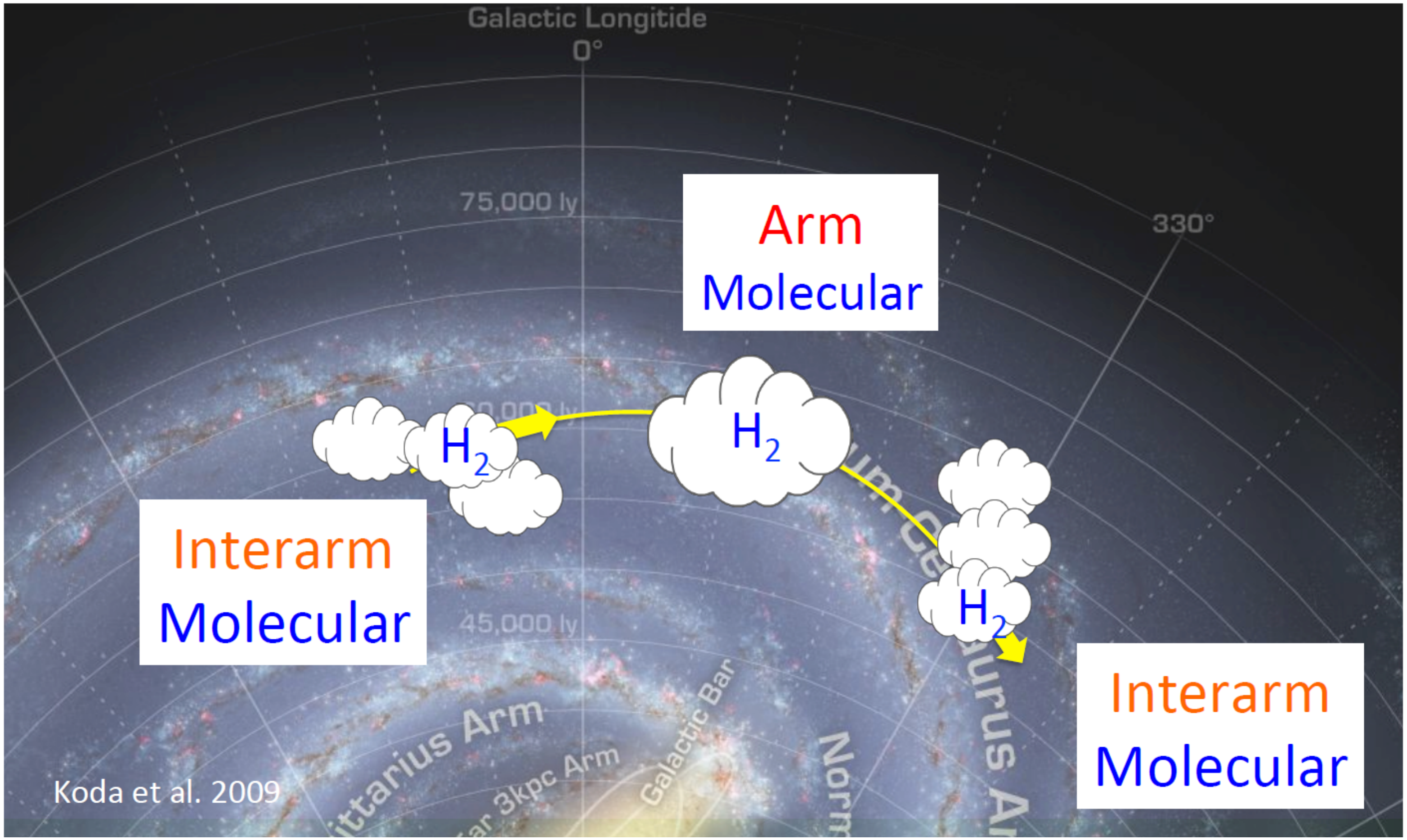
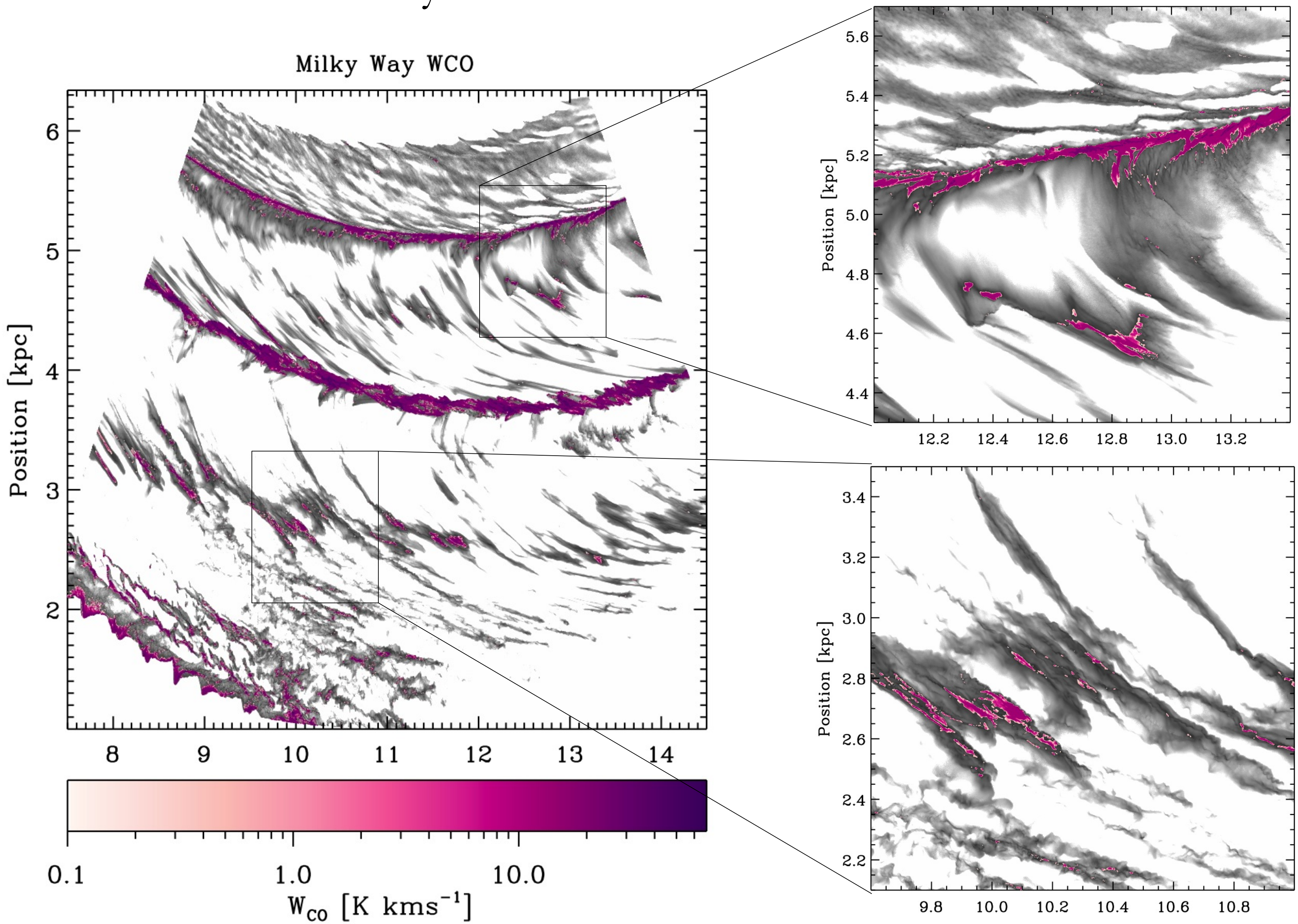


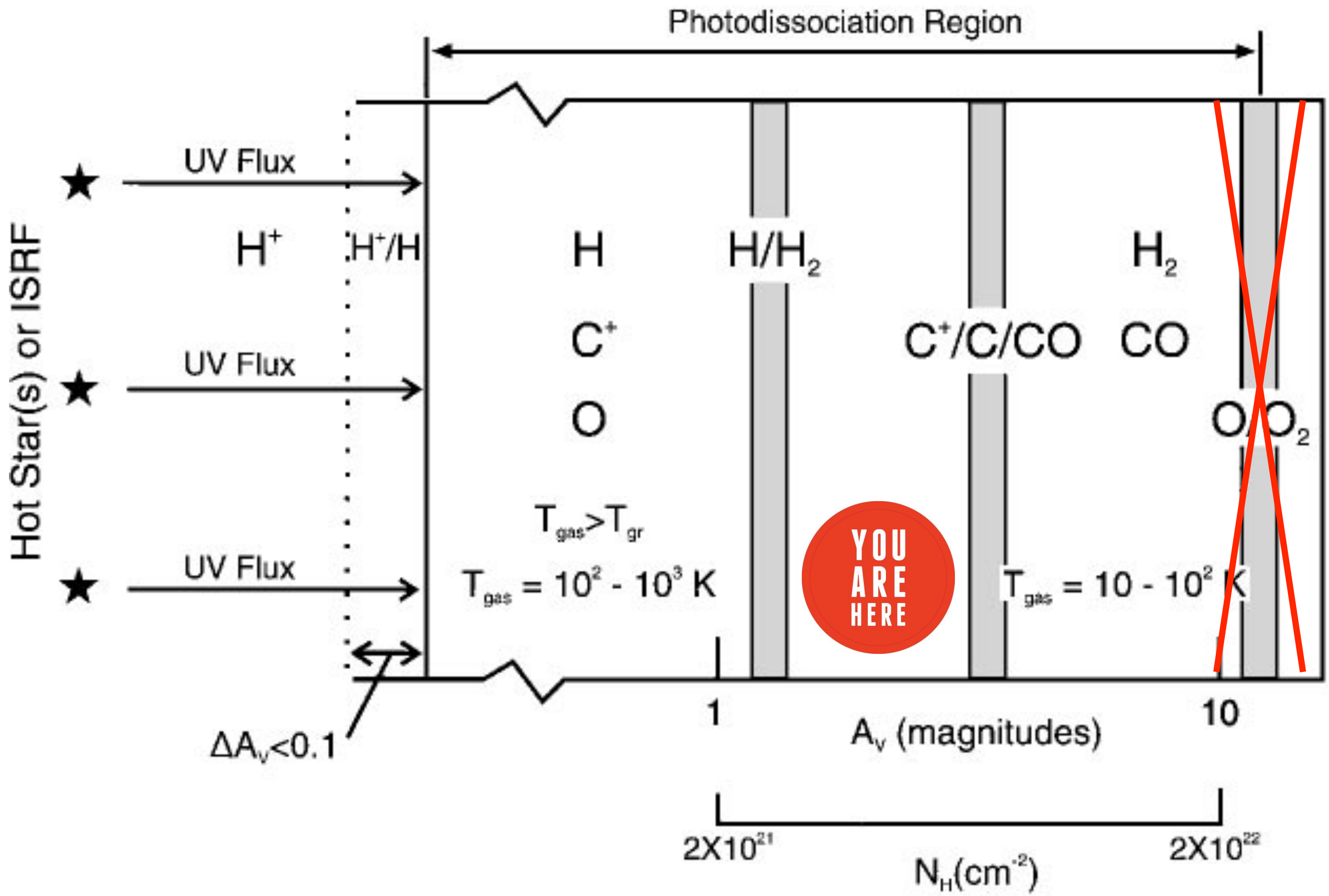
Image courtesy of Jin Koda

Grey-scale: Molecular Hydrogen H_2.
Color-scale: CO Intensity.



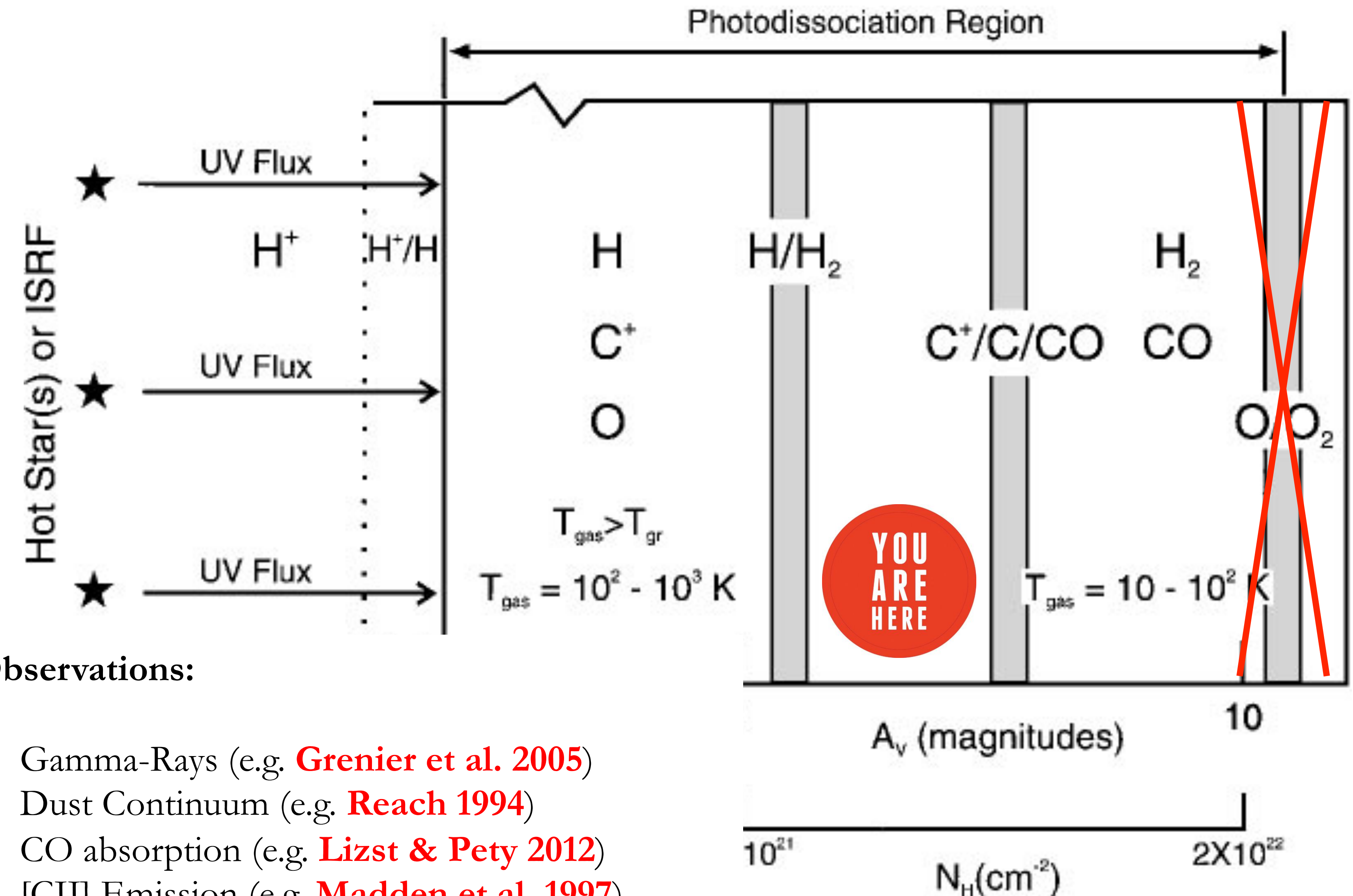
(Smith et al., 2014, MNRAS, 441, 1628)

CO-"Dark" H_2 Gas



Hollenbach and Tielens (1997)

CO-"Dark" H_2 Gas



Hollenbach and Tielens (1997)

Observations:

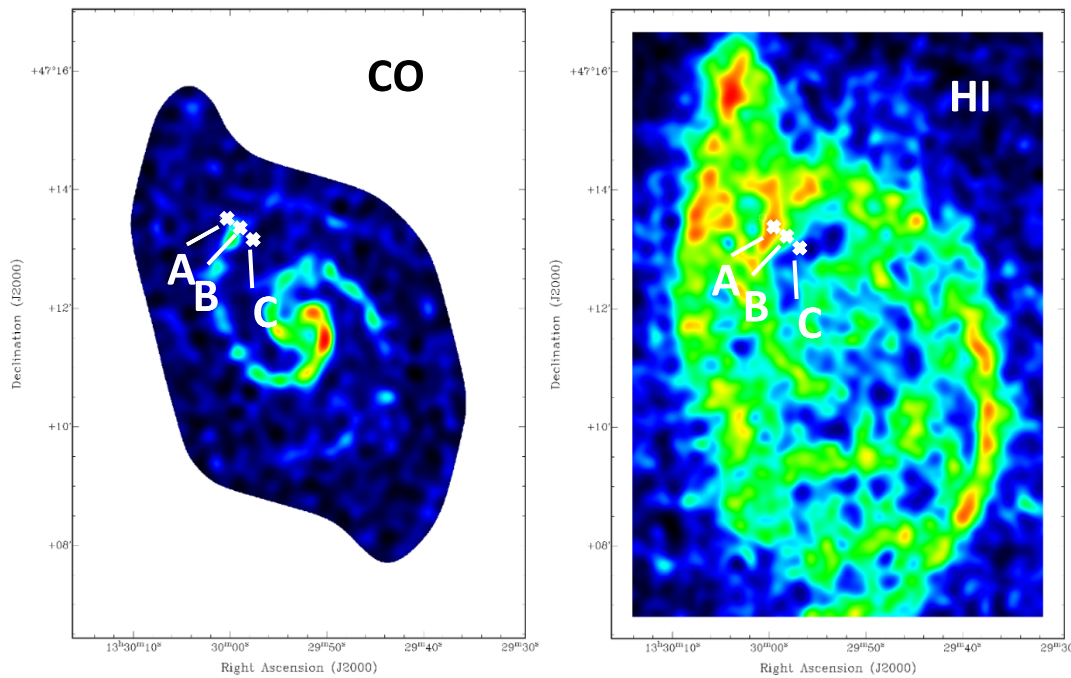
- Gamma-Rays (e.g. **Grenier et al. 2005**)
- Dust Continuum (e.g. **Reach 1994**)
- CO absorption (e.g. **Lizst & Pety 2012**)
- [CII] Emission (e.g. **Madden et al. 1997**)

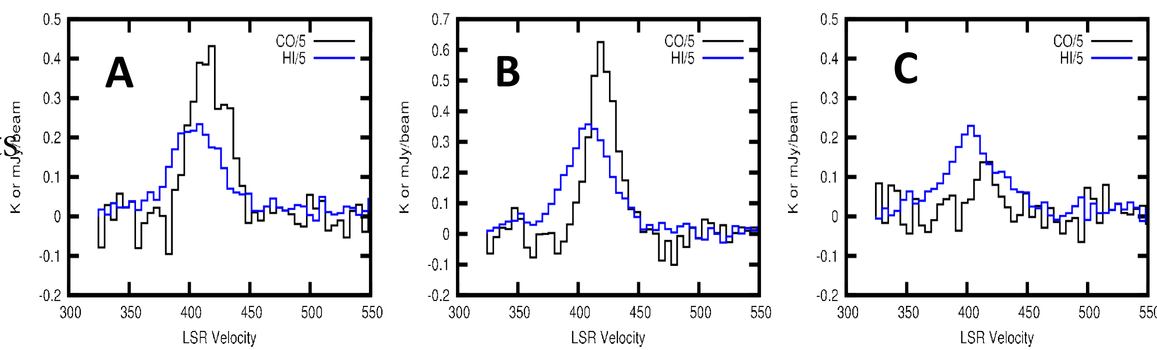
Observations of all ISM and stellar components are needed to understand the lifecycle of the ISM.

To truly understand galactic disks, we need a full understanding of the spiral structure and the interrelation between the all the gaseous and stellar components, and their connection to the star formation process.

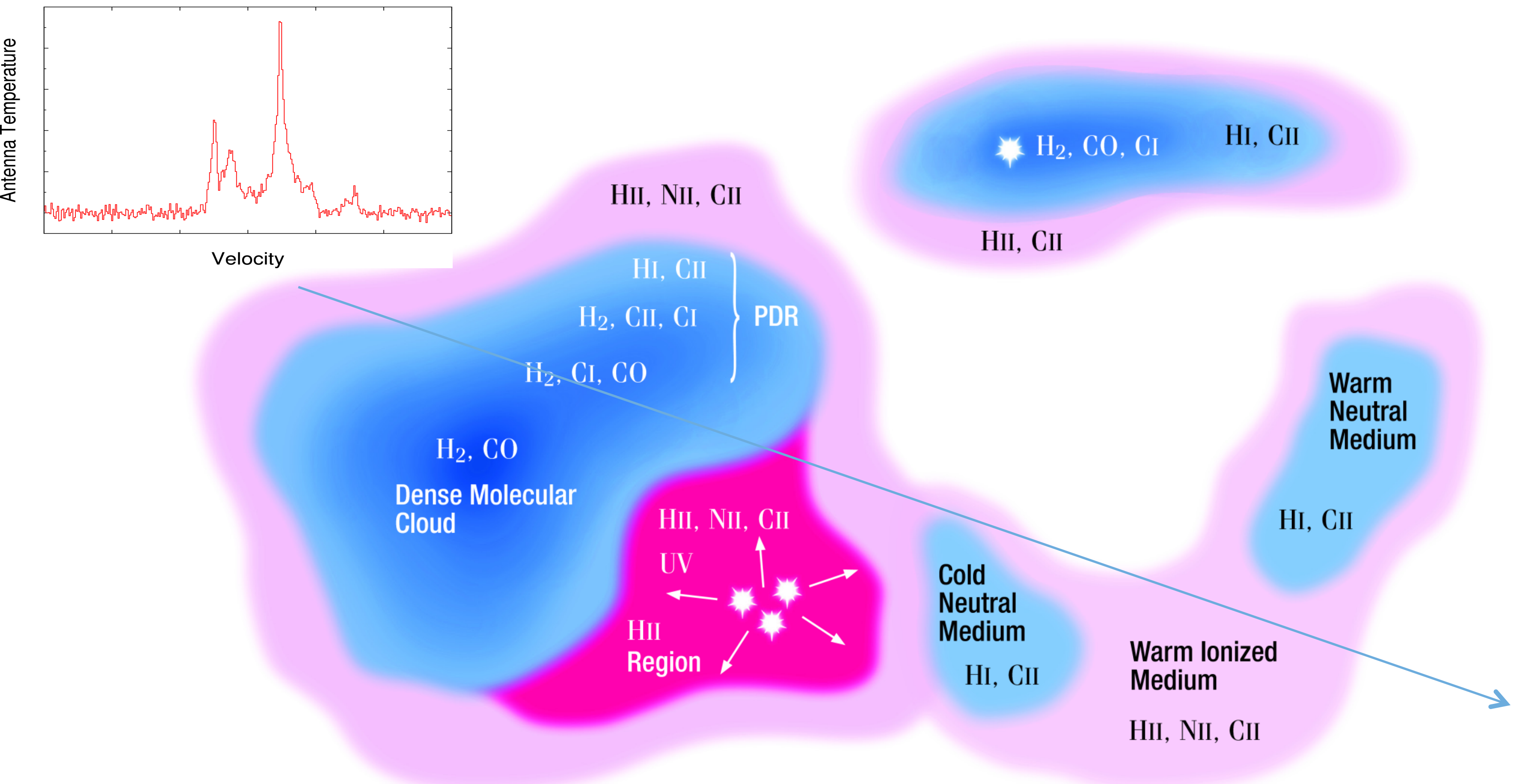
Velocity resolved observations are needed to separate the different phases of the ISM in spiral arms so we can study the upstream and downstream parts of the spiral arms via their different velocities.

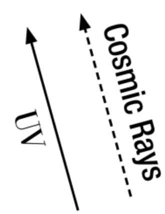
We can study the compression of molecular gas and the onset and effects of star formation at the downstream side of the spiral arms.





[CII] traces the different phases of the ISM

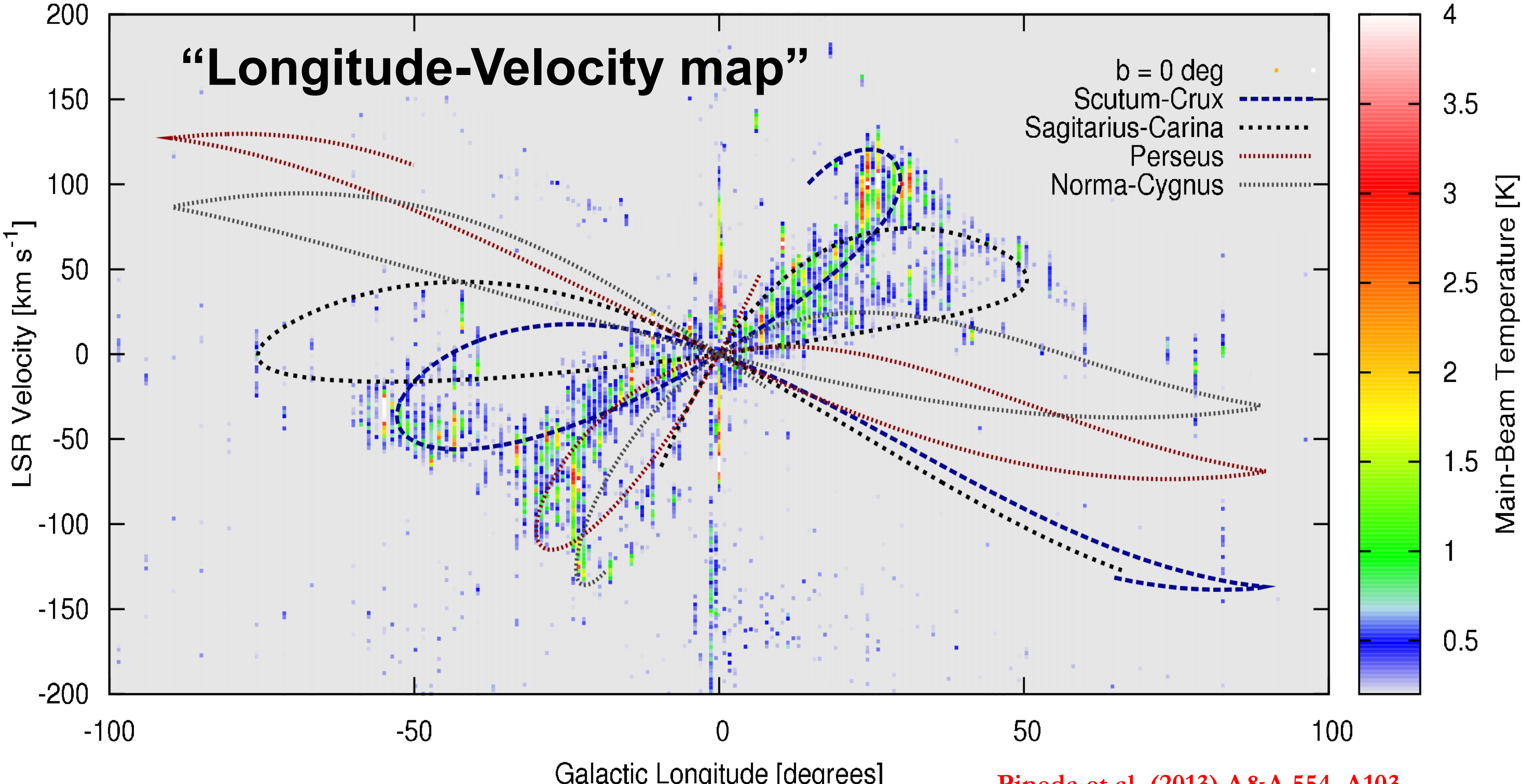




[CII] can be excited by collisions with:

- Electrons.
- Atomic Hydrogen.
- Molecular Hydrogen (dense or diffuse).

First observation of the line-of-sight [CII] distribution of the Milky Way (Herschel):

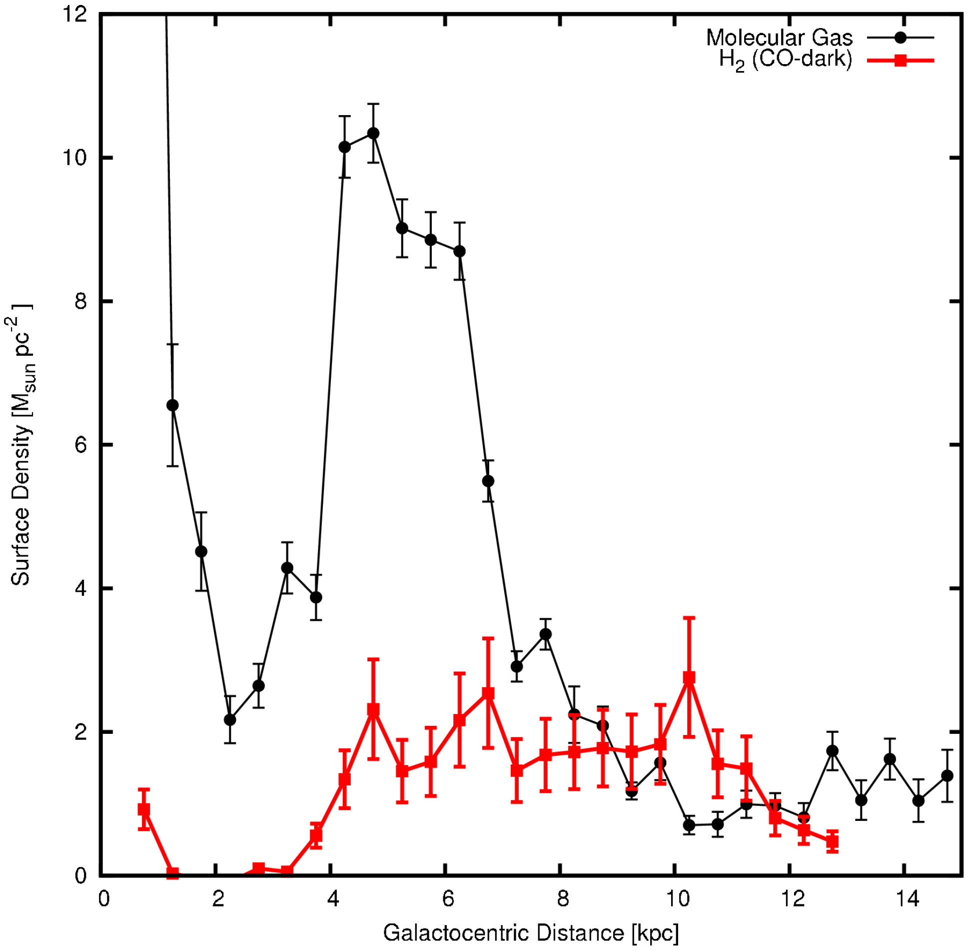


Pineda et al. (2013) A&A 554, A103

The lines are projection of the Milky Way's spiral arms into the Longitude-Velocity map.

The distribution of the CO-dark H_2 gas in the Milky Way

- The known molecular gas (traced by CO and ^{13}CO) in the Milky Way is concentrated between 3 to 8 kpc from the galactic center.
- The CO-dark H_2 gas extends to larger distances from the galactic center.
- On average, CO-dark H_2 represents about 30% of the total molecular mass in the Milky Way.

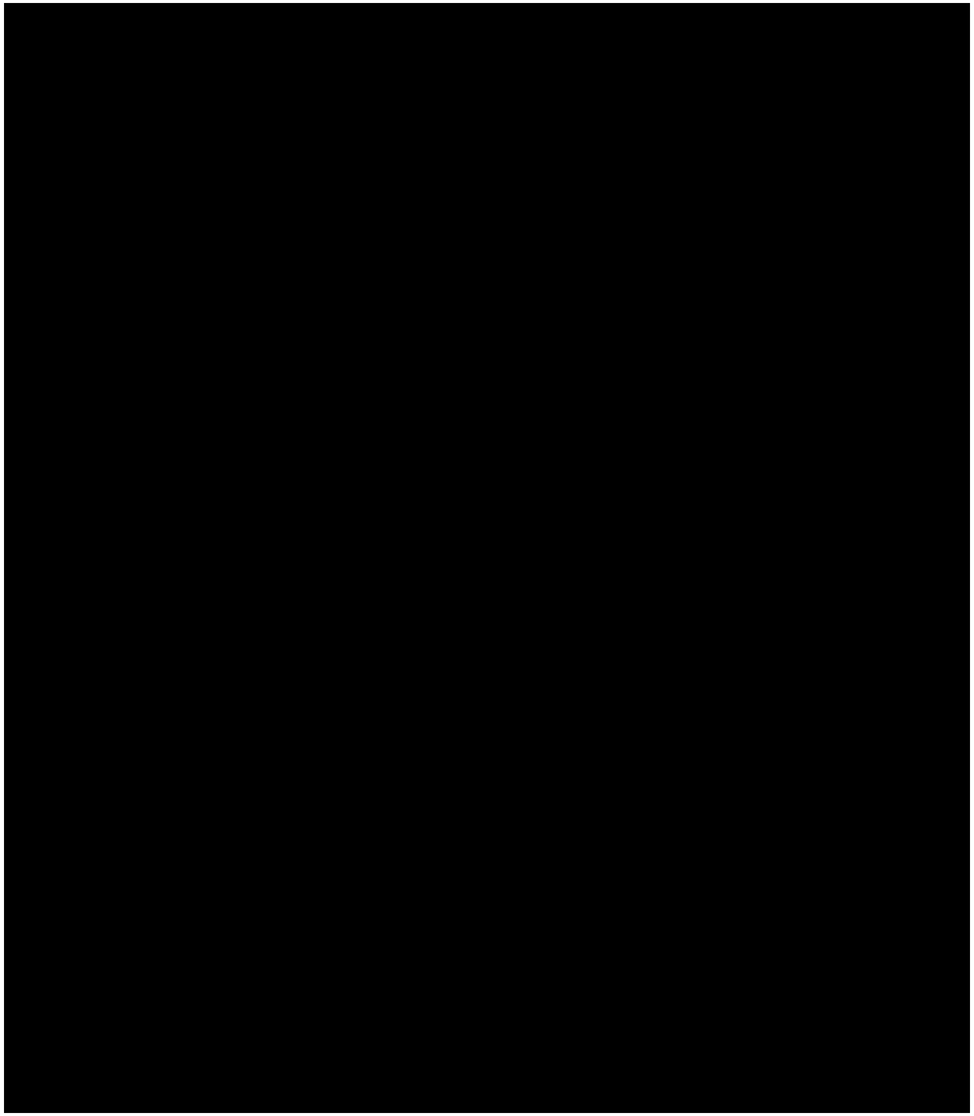


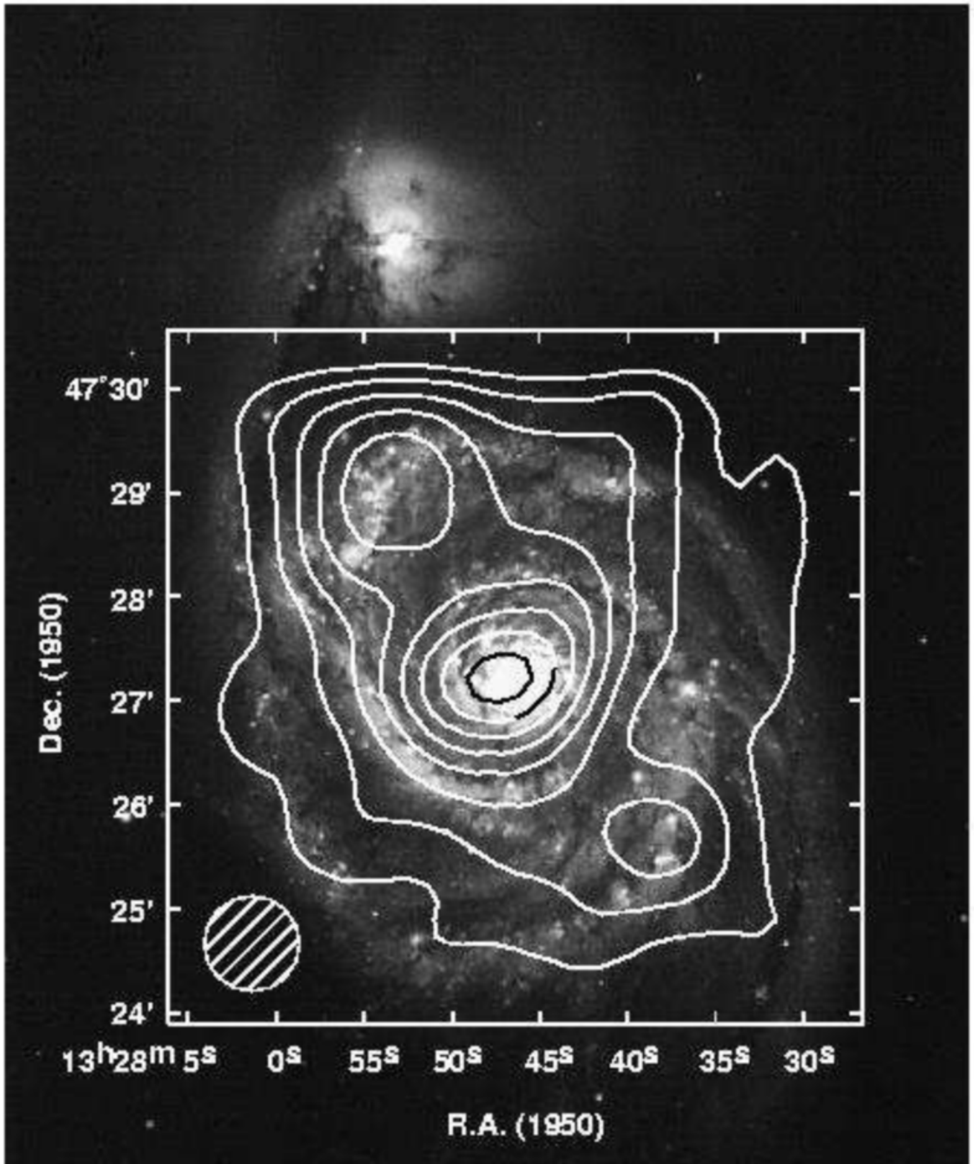
Pineda et al. (2013) A&A 554, A103

Mapping [CII] in galaxies is needed.

We need [CII] maps of entire galaxies with angular resolution sufficient to separate arm from inter-arm regions **and** with enough velocity resolution to separate the phases of the ISM across spiral arms.

SOFIA will provide for the first time such a map.





KAO Observations of [CII] in M51

Nikola, T., et al. 2001, ApJ, 561, 203

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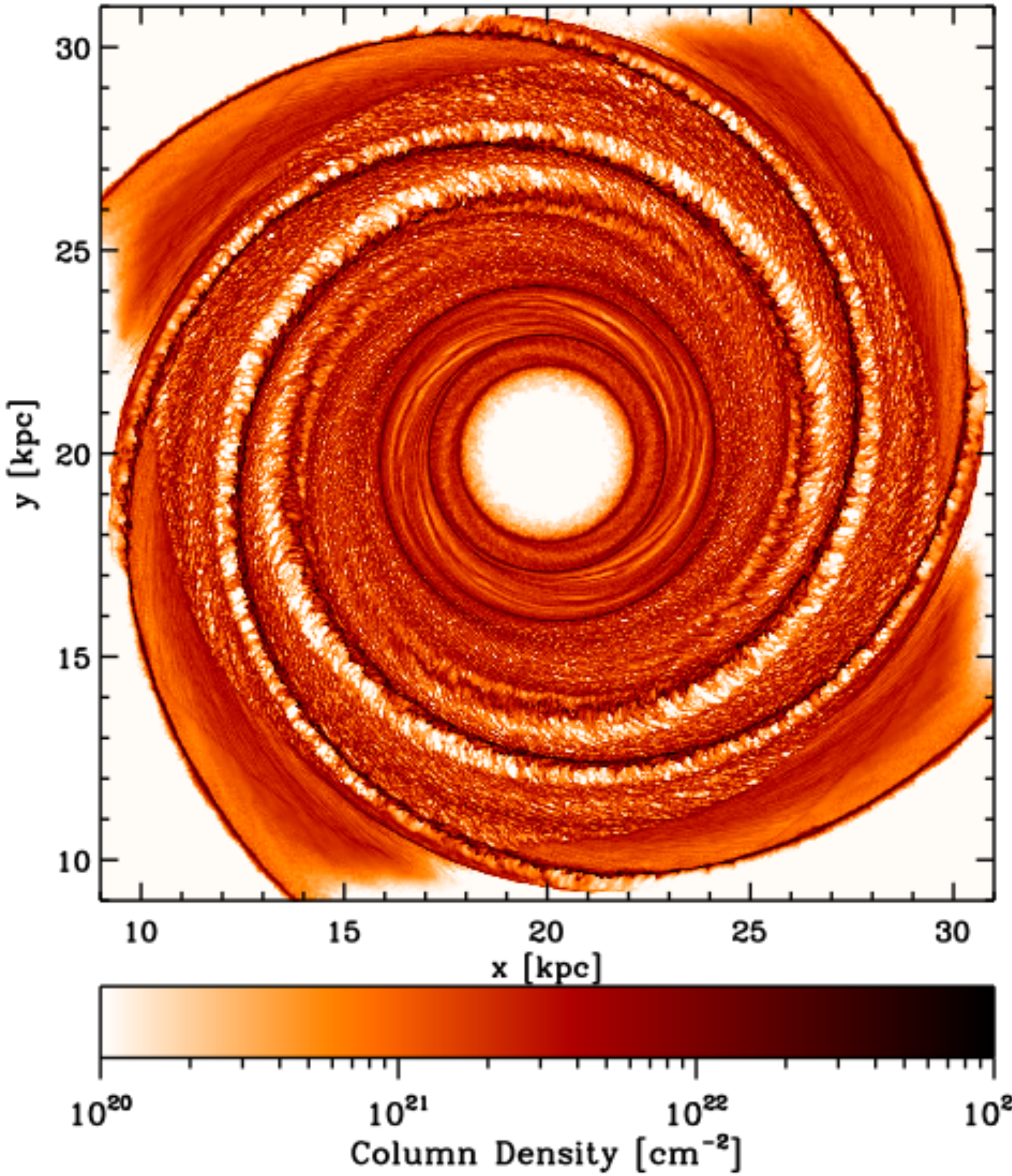
SOFIA [CII] Mapping of M51

- Joint impact project between US and German institutions.
- 75h of observing time over Cycle 4 and 5.
- 80% US time and 20% German time.
- **upGREAT** observations for resolving the spiral arms in velocity space.
- **FIFI-LS** observations for sensitive observations of [CII] in the inter-arm regions.
- First complete maps March 2017, first publications mid-2017.
- Expected completion, February 2018.

SOFIA [CII] Mapping of M51: Science Goals

- Study the effect of spiral arms in the evolution of the ISM and star formation
- Separate the different ISM phases in spiral arms (velocity space).
- Determine the physical conditions of the line-emitting gas over different environments.
- Image the distribution of CO-dark H_2 gas across M51. In particular in the inter-arm regions.

The SOFIA map will be directly compared with theoretical model of the ISM in M51.



at t = 190 Myr

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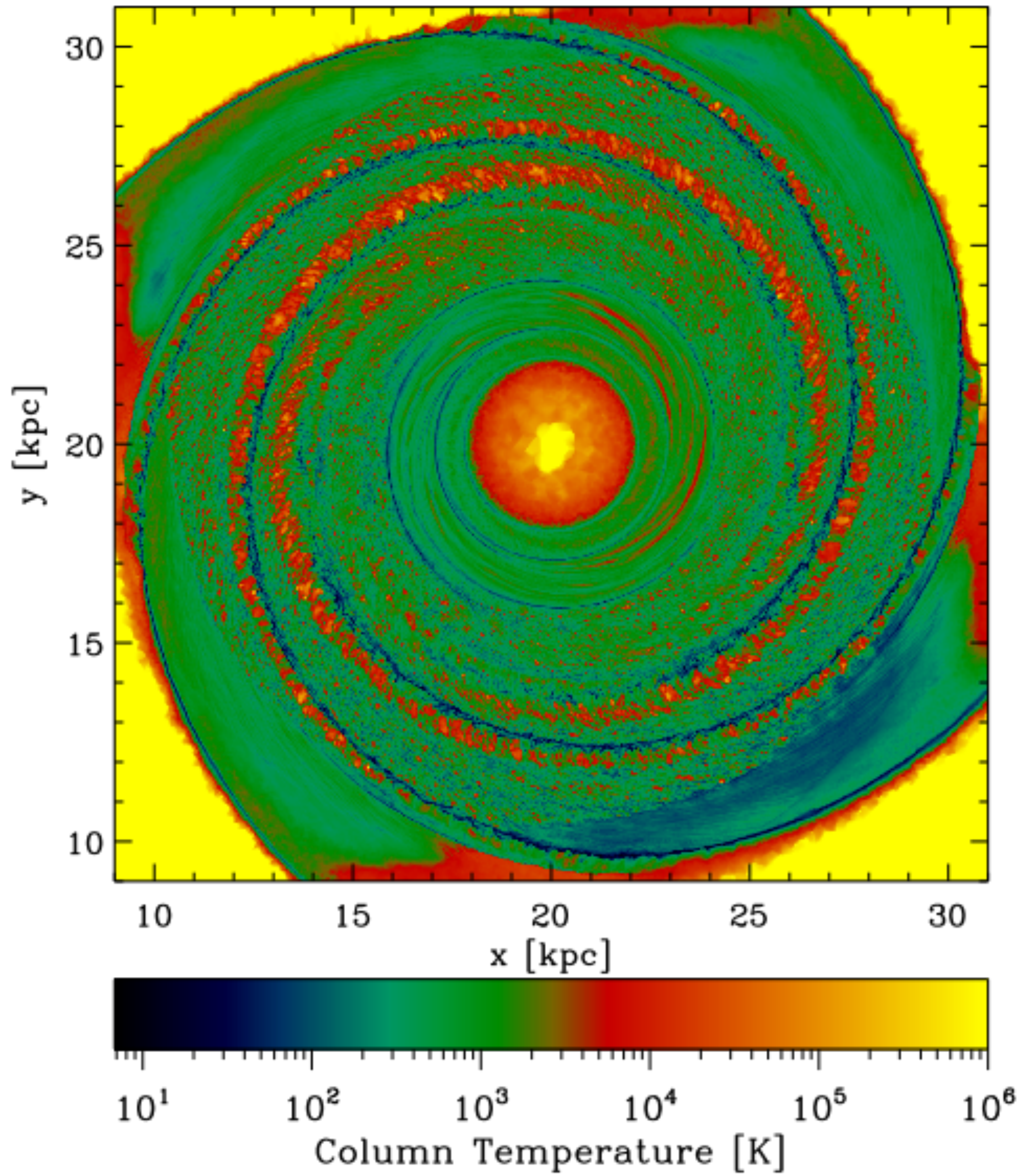

at t = 190 Myr

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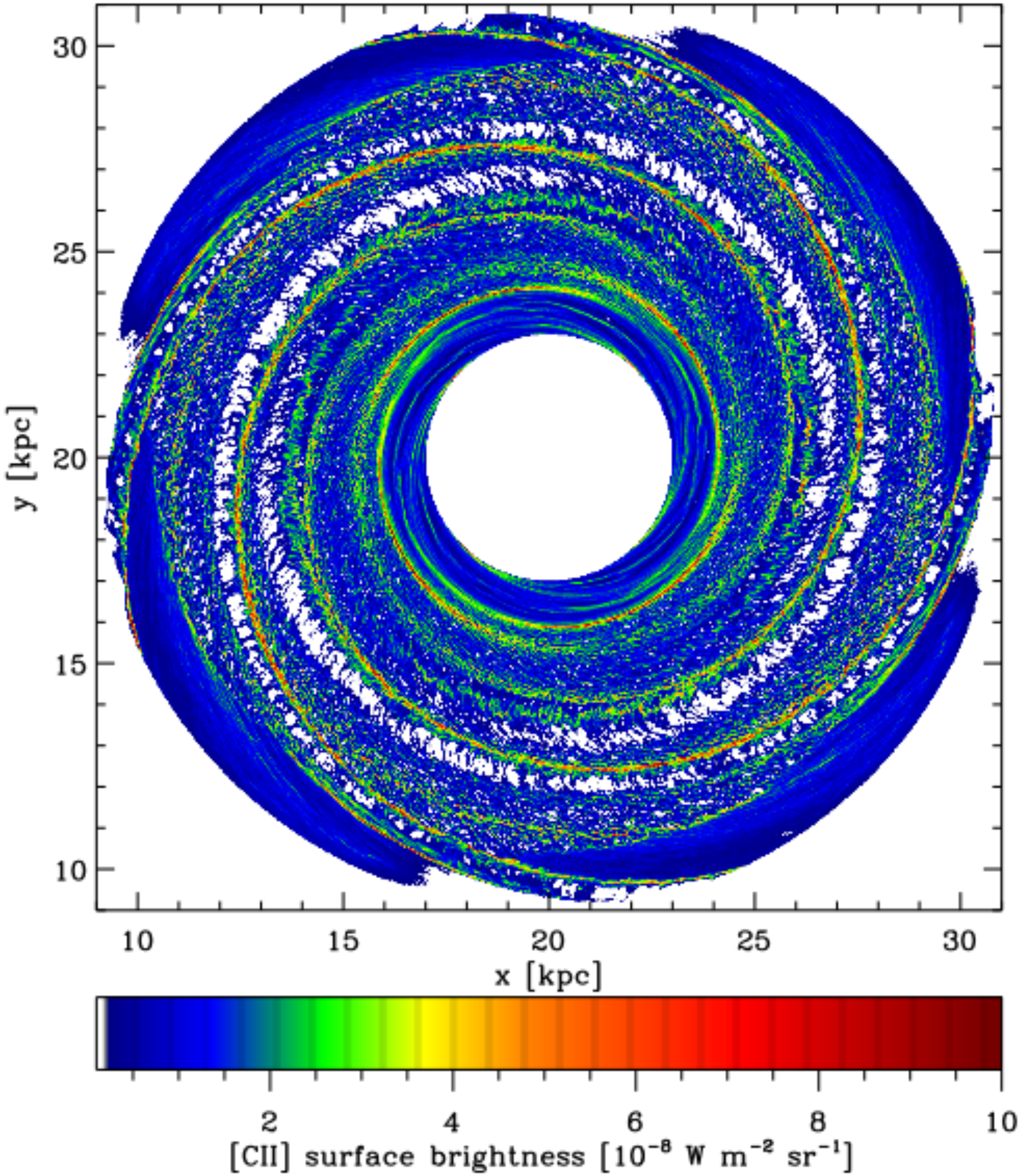
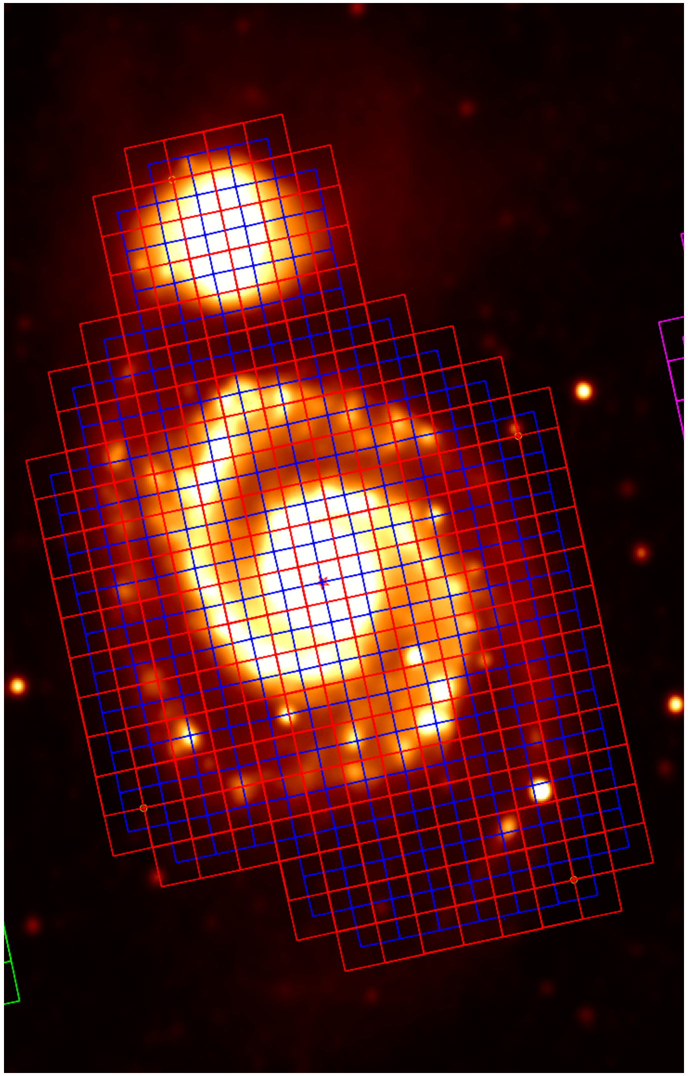
We will test the prediction of a large amount of CO-dark H_2 in the inter-arm regions.

at t = 190 Myr



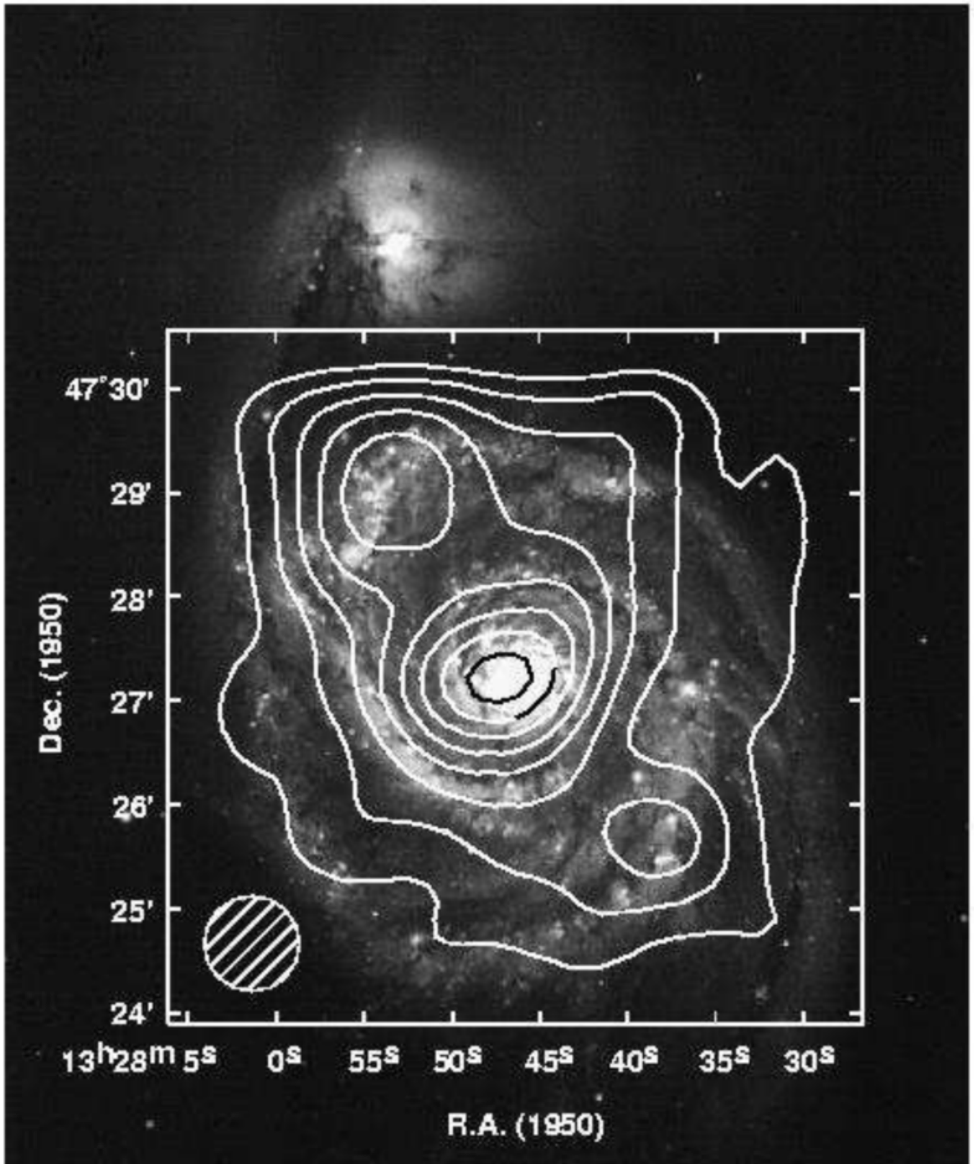
FIFI-LS coverage



upGREAT coverage

SOFIA [CII] Mapping of M51: Status

- 6h (50%) of **FIFI-LS** allocated; ½ of the map completed.
- 8h (13%) of **upGREAT** allocated; 1/10 of the map completed.



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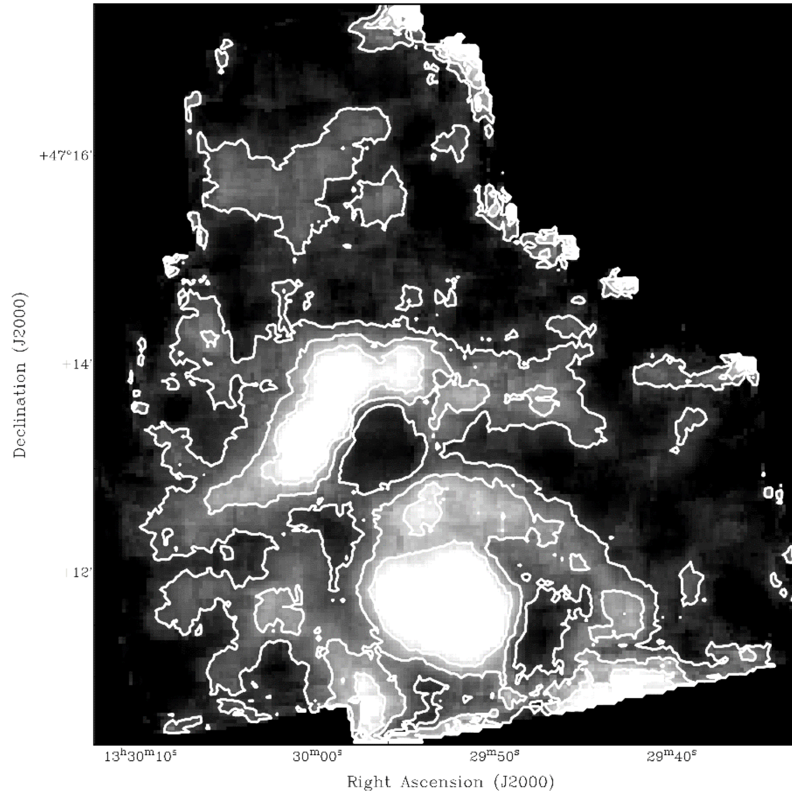
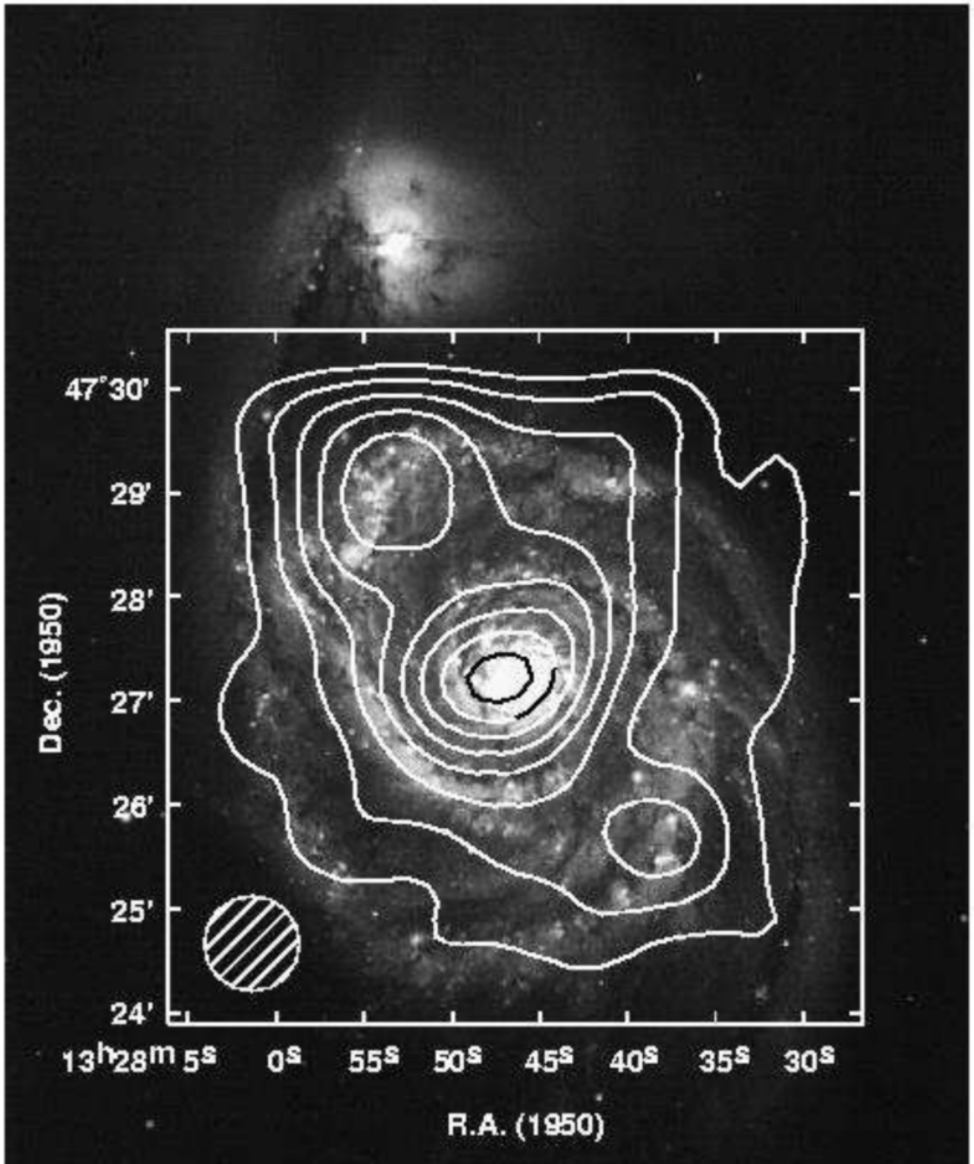
SOFIA/FIFI-LS Observations of [CII] in M51





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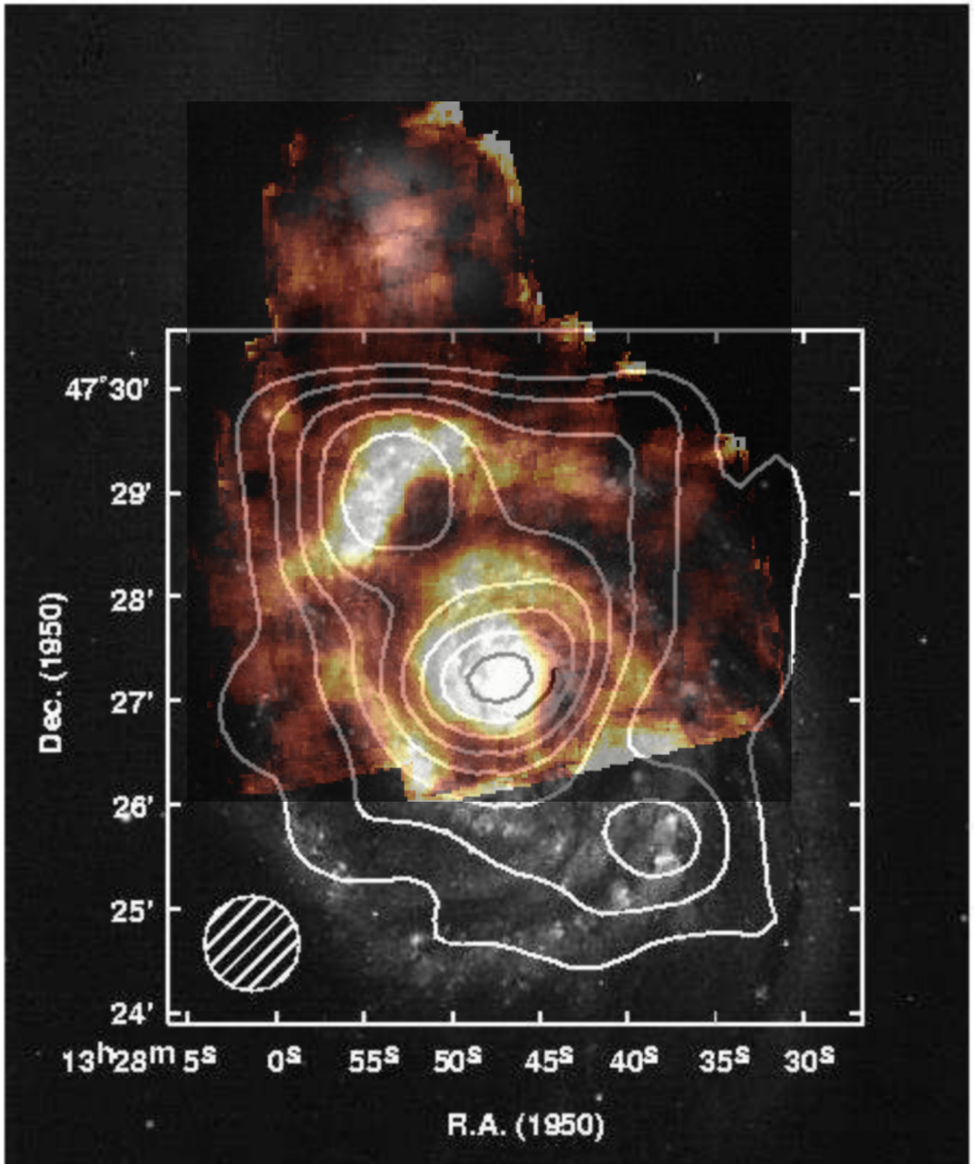

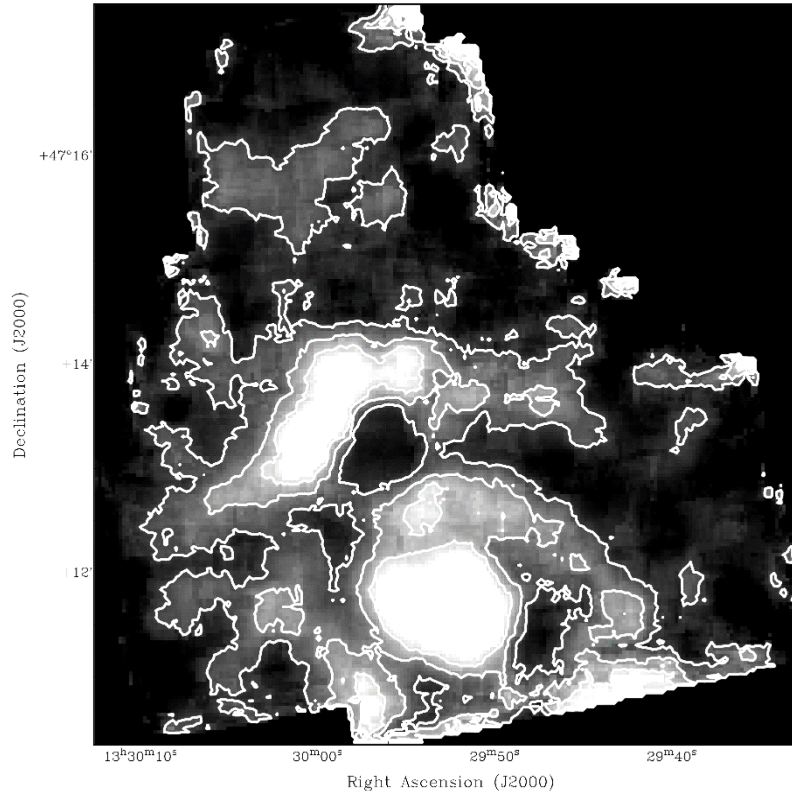

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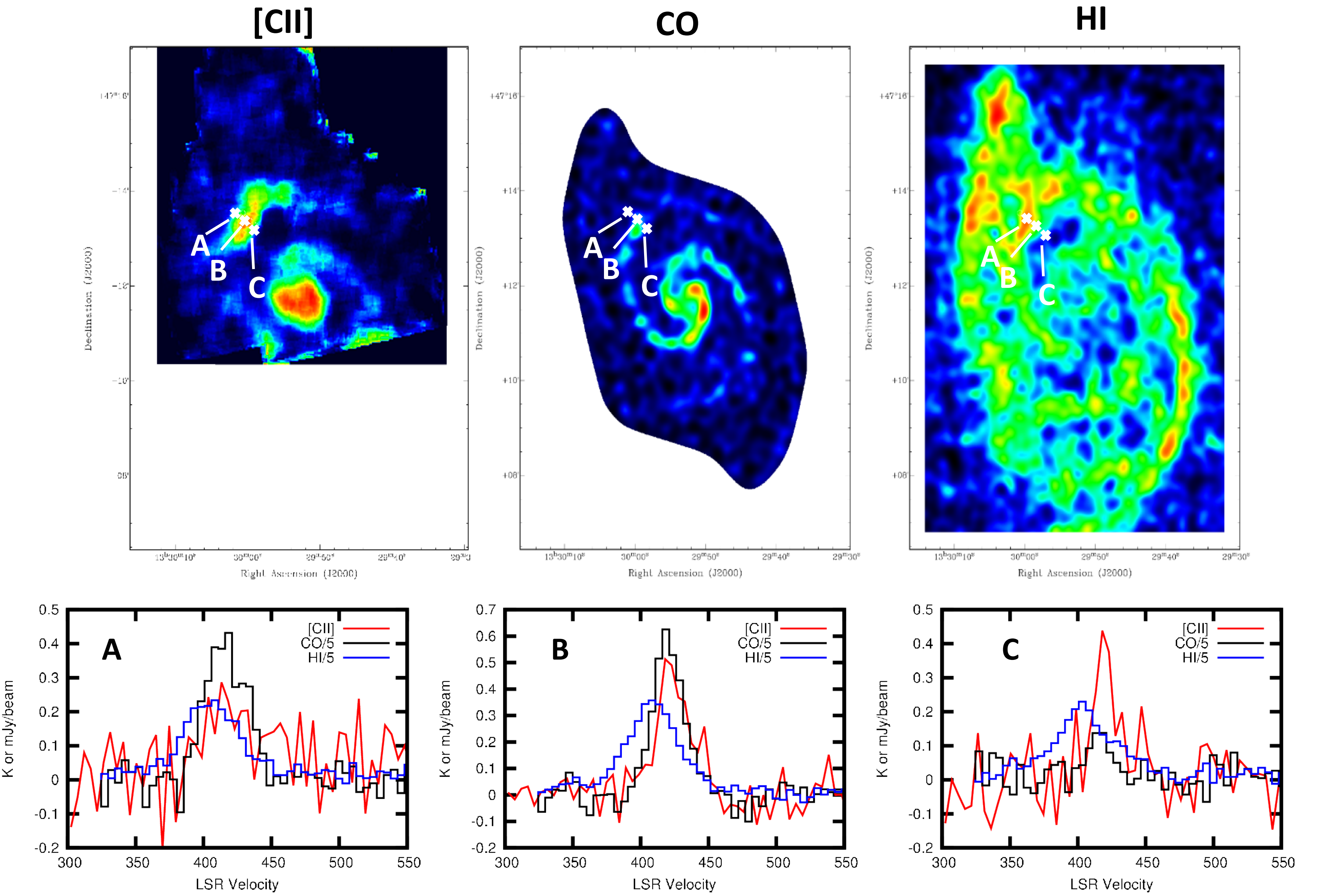
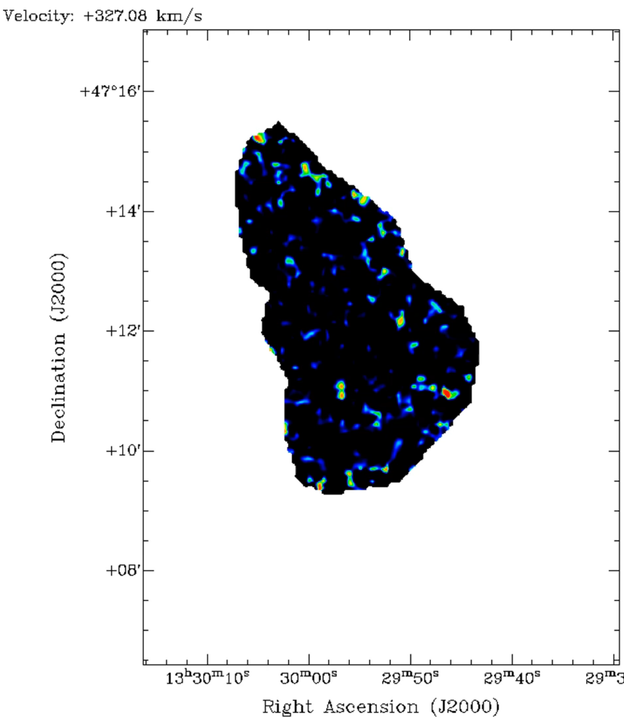
[CII], CO, HI Integrated Intensity Maps

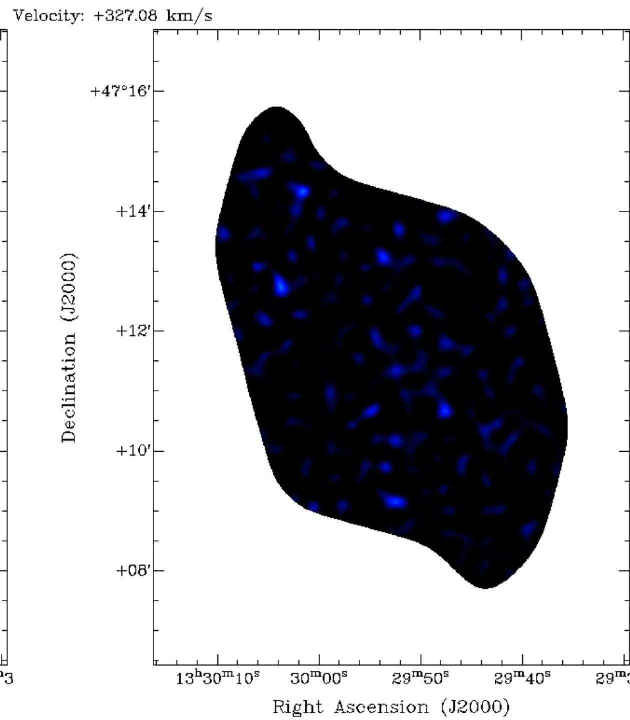


[CII], CO, HI Channel Maps

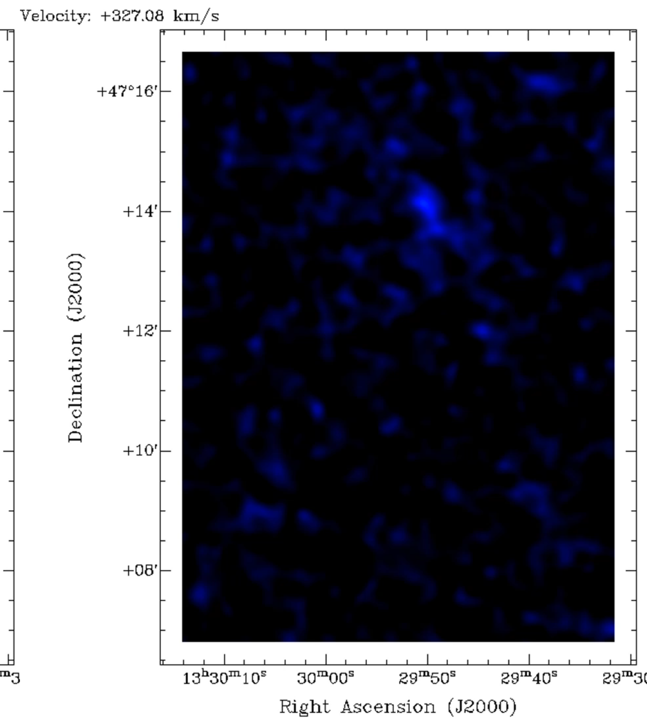
[CII]

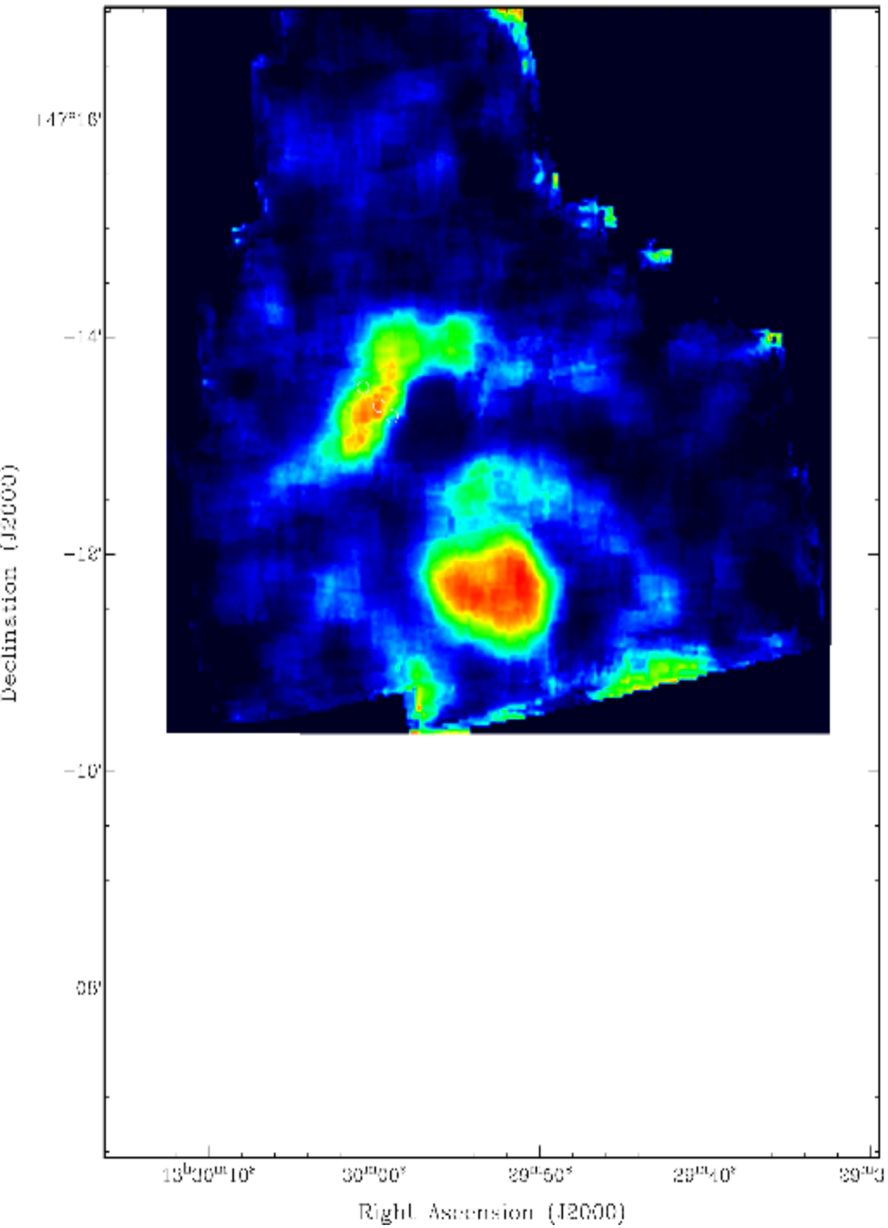


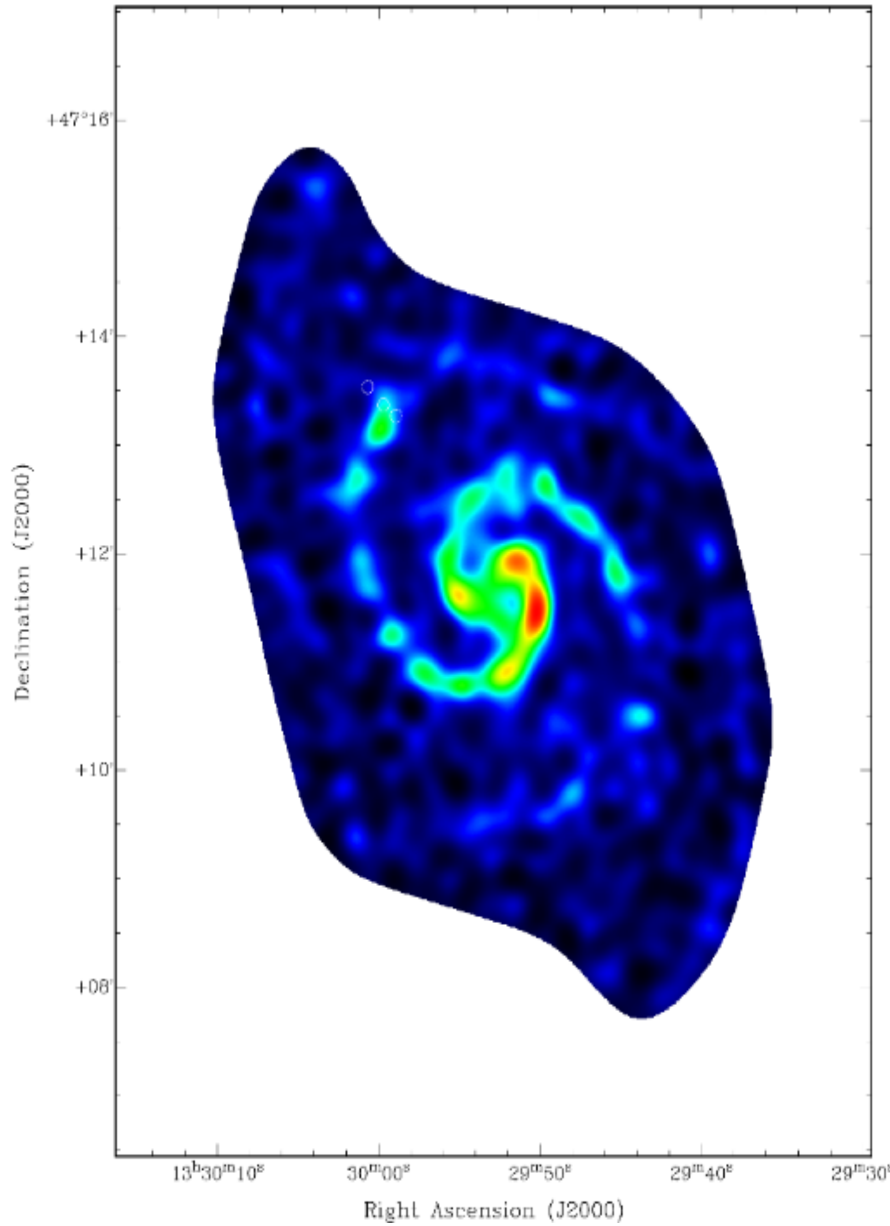
CO



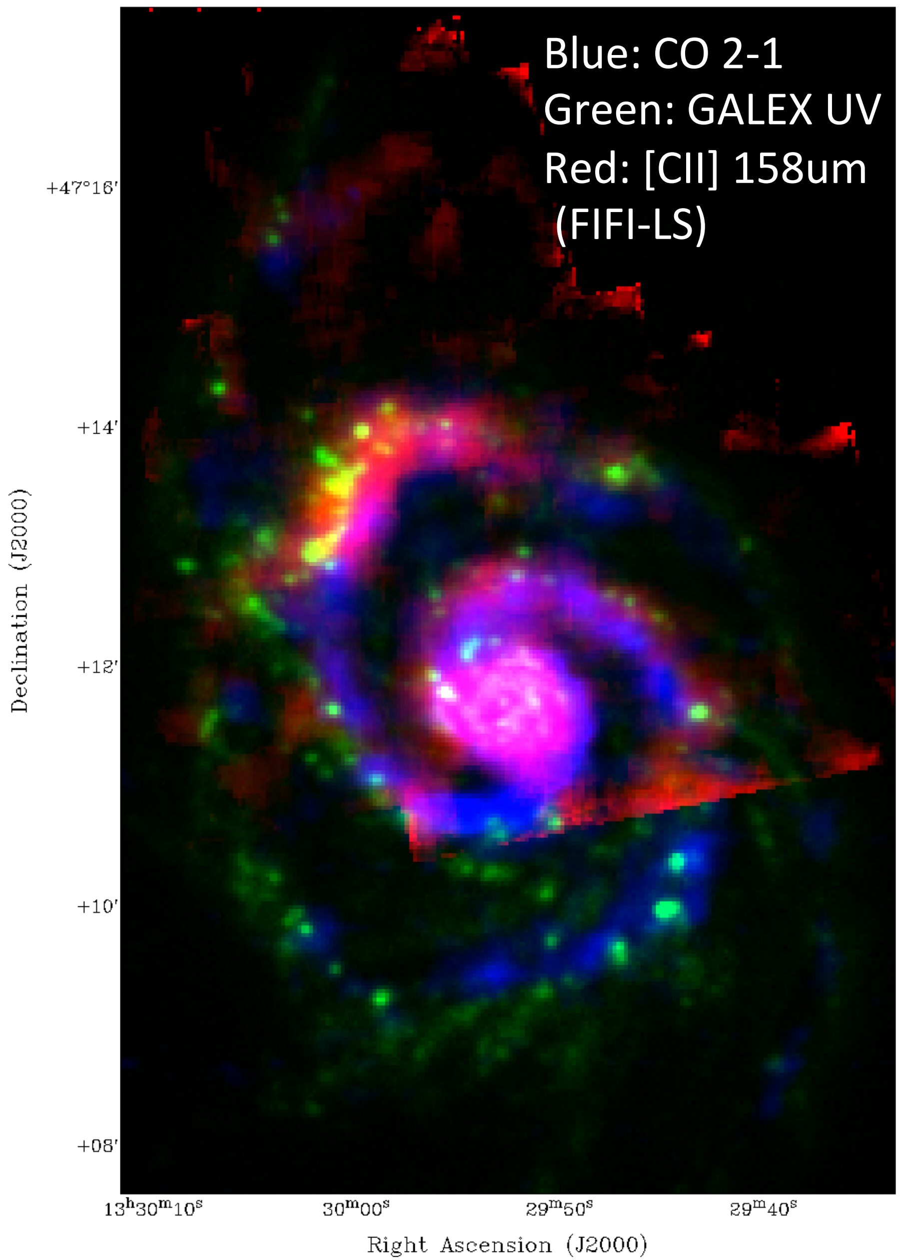
HI



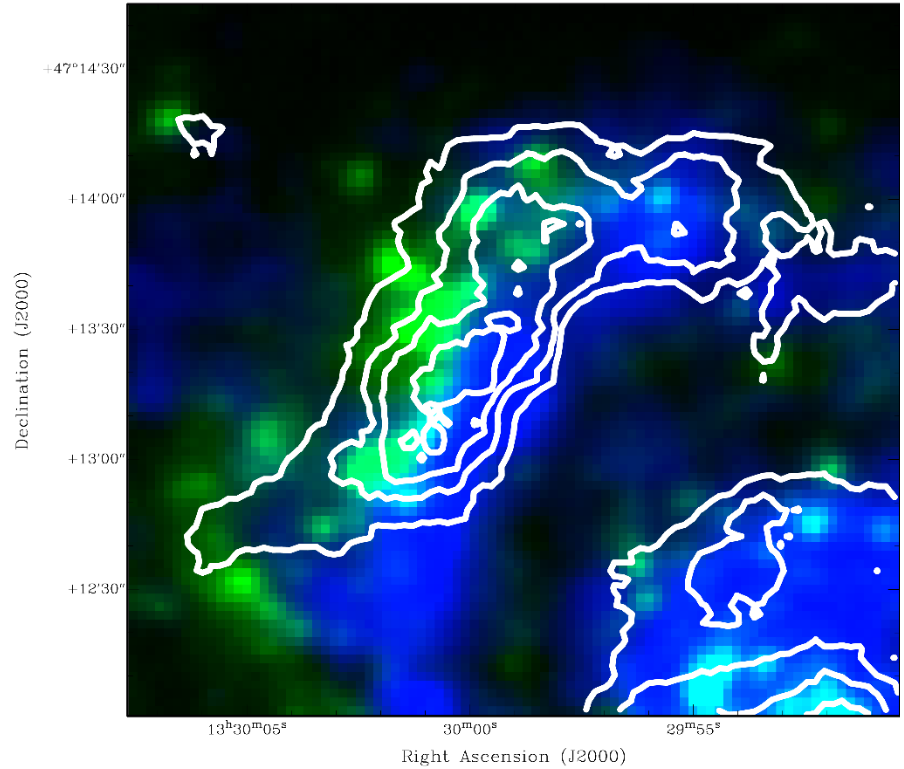

Declination (J2000)
Right Ascension (J2000)


+47°16'
+14'
+12'
+10'
+08'
Declination (J2000)
$13^h30^m10^s$
30^m00^s
29^m50^s
29^m40^s
29^m30^s
Right Ascension (J2000)

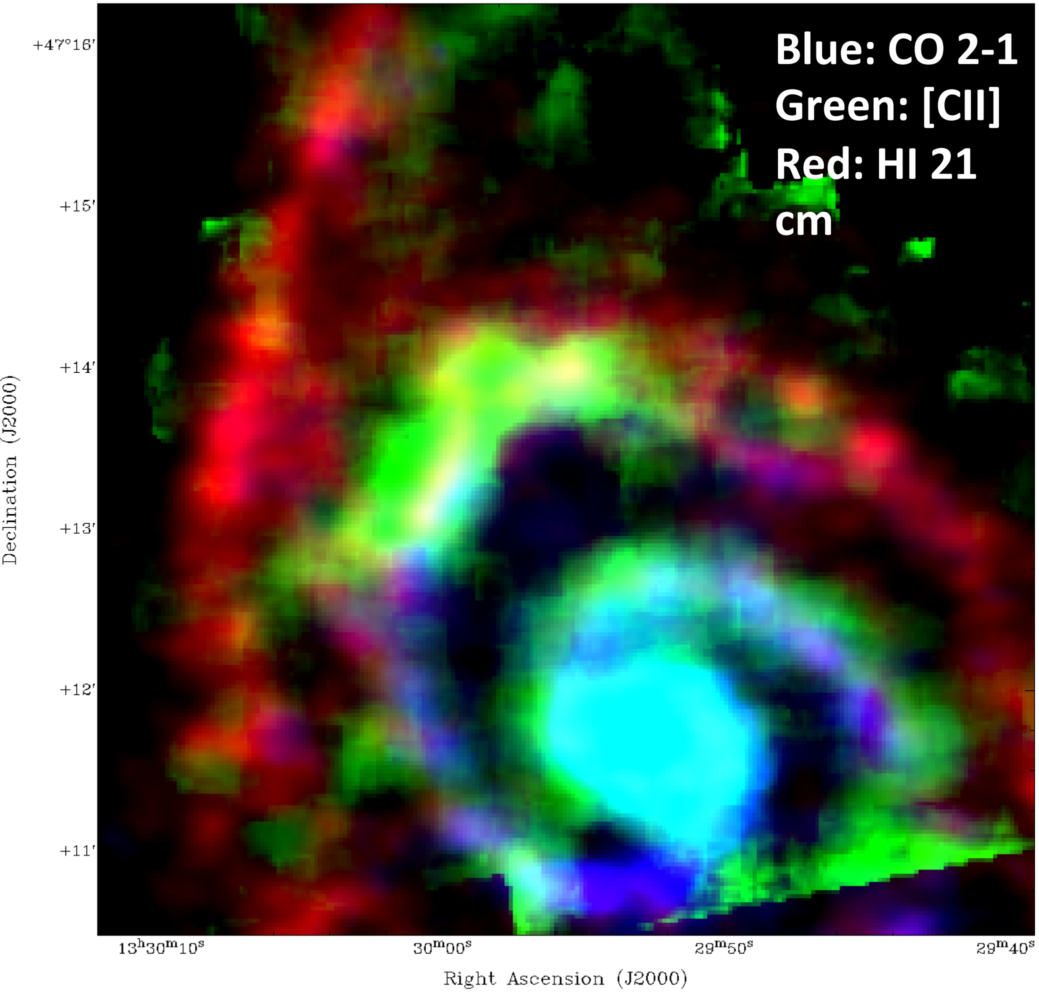
[CII] data highlights



- There are spatial offsets between UV, [CII], and CO observations.
- [CII] peaks between the UV and CO emission.

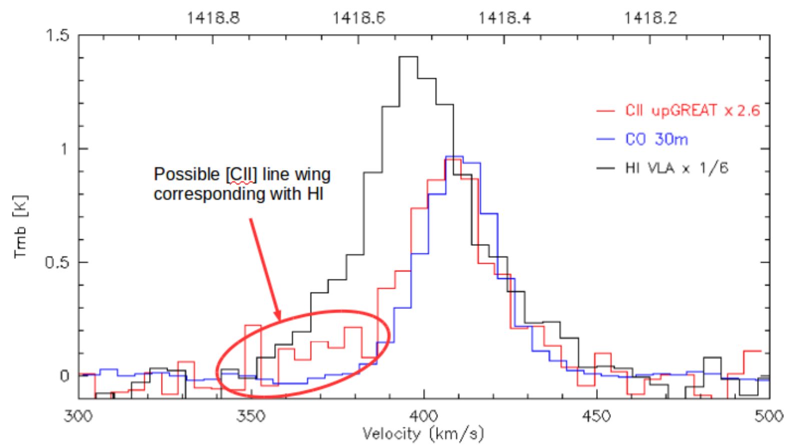


[CII] map highlights



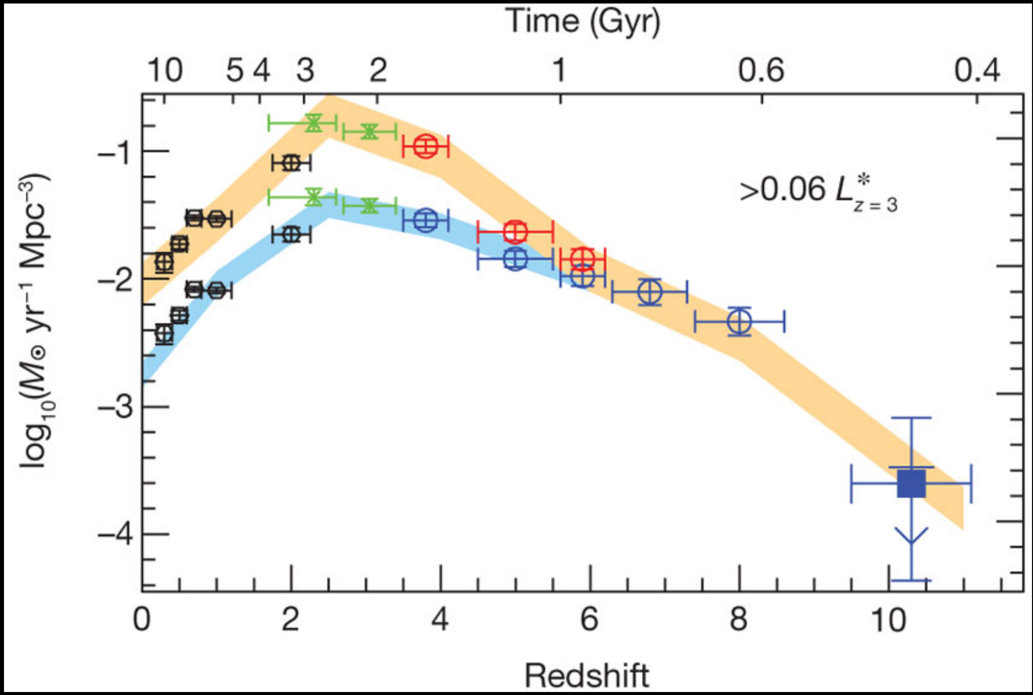
- [CII] emission is seen in HI holes.
- Possible evidence of outflows seen in [CII] and HI.
- We could be tracing stellar Feedback.

- [CII] emission is present in inter-arm regions.



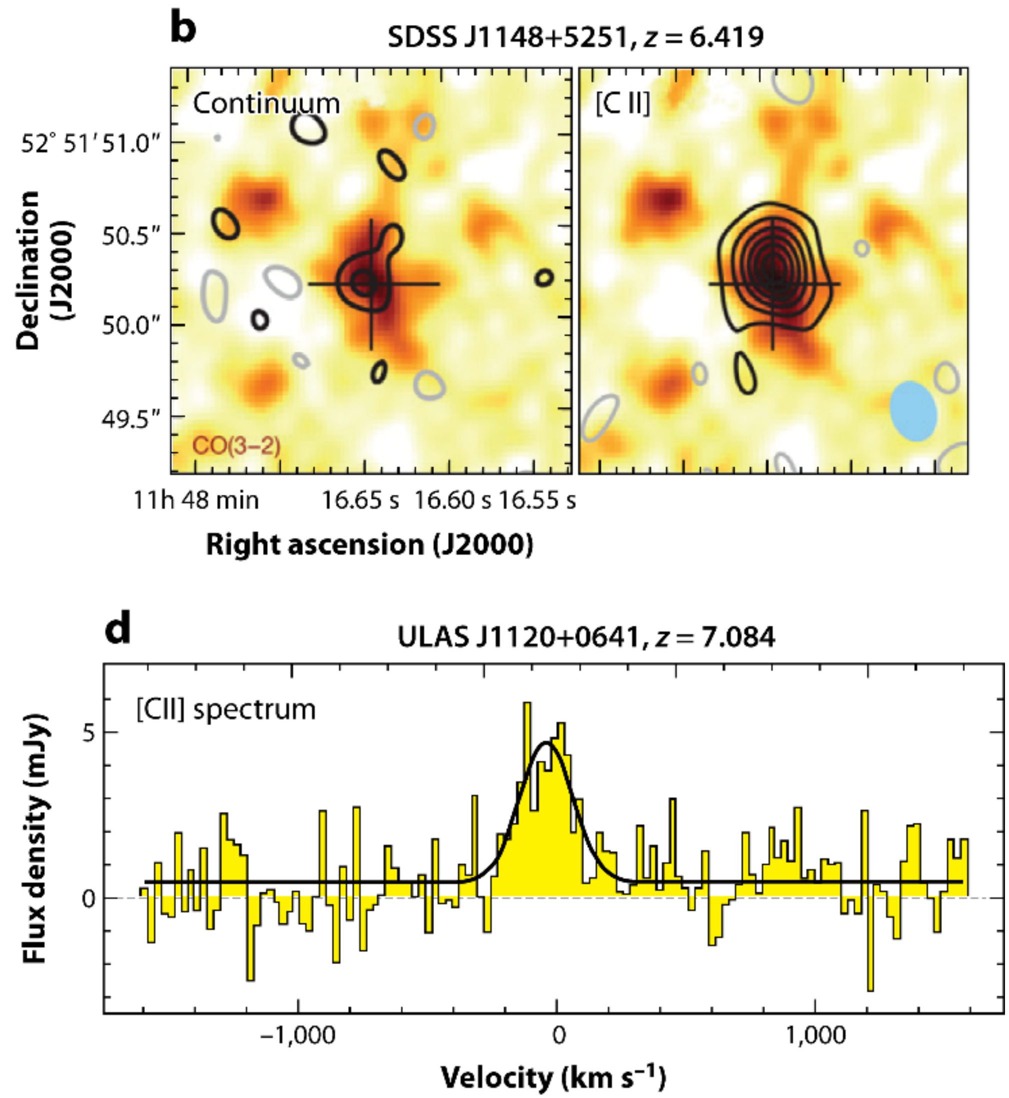
The star formation rate

- An important parameter used to characterize star formation in galaxies over cosmic time.
- Measured in units of solar masses per year.
- The peak of star formation in the Universe occurred at redshift Z=2.
- It is important to find tracers of star formation that can be observed in galaxies over a wide range of redshifts.



[CII] is also a tracer of the Star Formation Rate

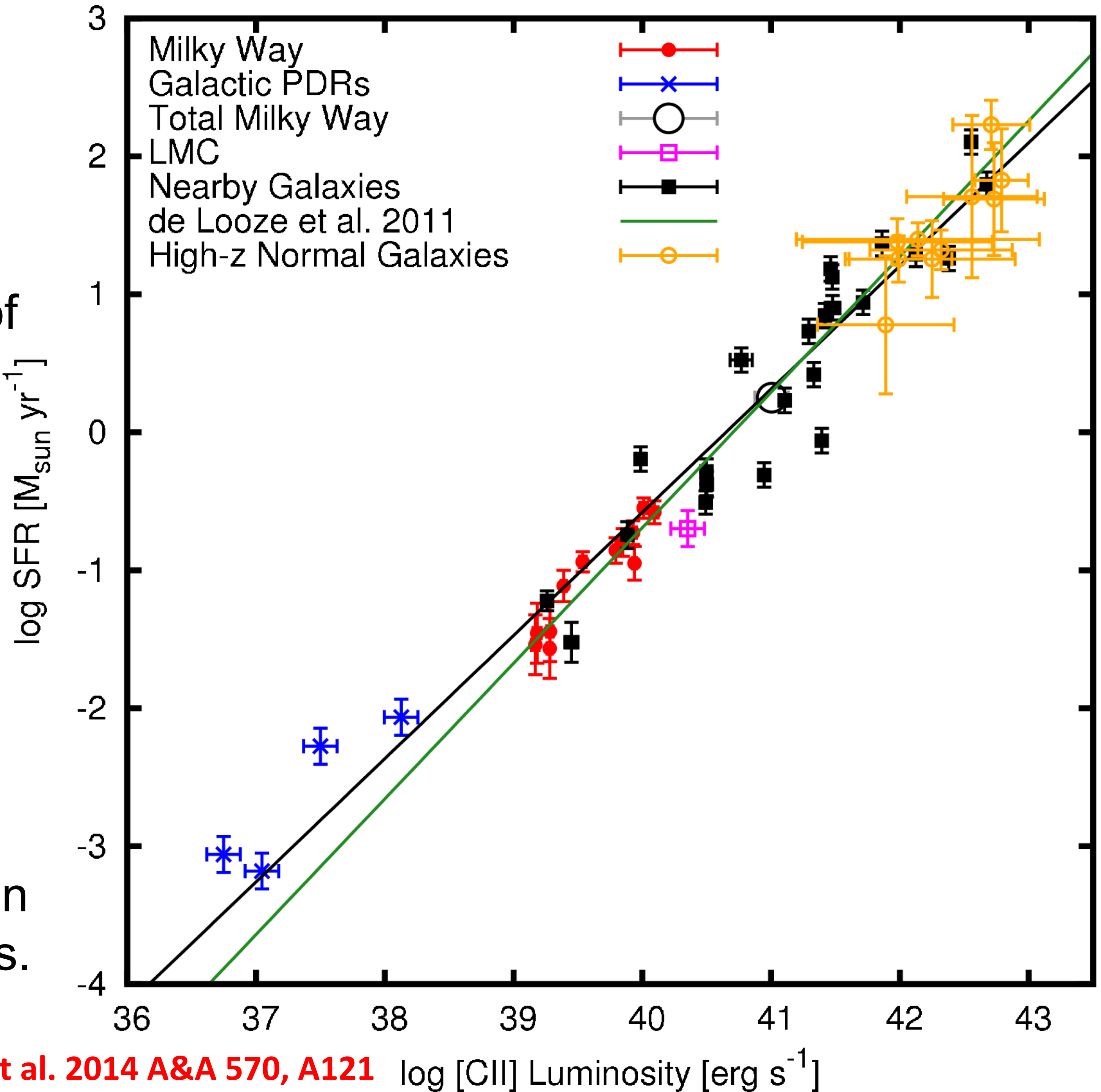
- FUV photons from massive stars heat the gas via Photoelectric heating.
- [CII] is one of the main coolants of the ISM.
- [CII] luminosity is then related to the energy input of star formation to the ISM.
- As a result it is the brightest FIR line, representing 0.1% to 1% of the total FIR continuum (that's a lot).
- It is important to understand the relation between [CII] and star formation in the Milk Way.



Wang et al. 2013 ApJ 773, 44

[CII] and star formation rate as correlated over 6 orders of magnitudes going from individual clouds to entire galaxies.

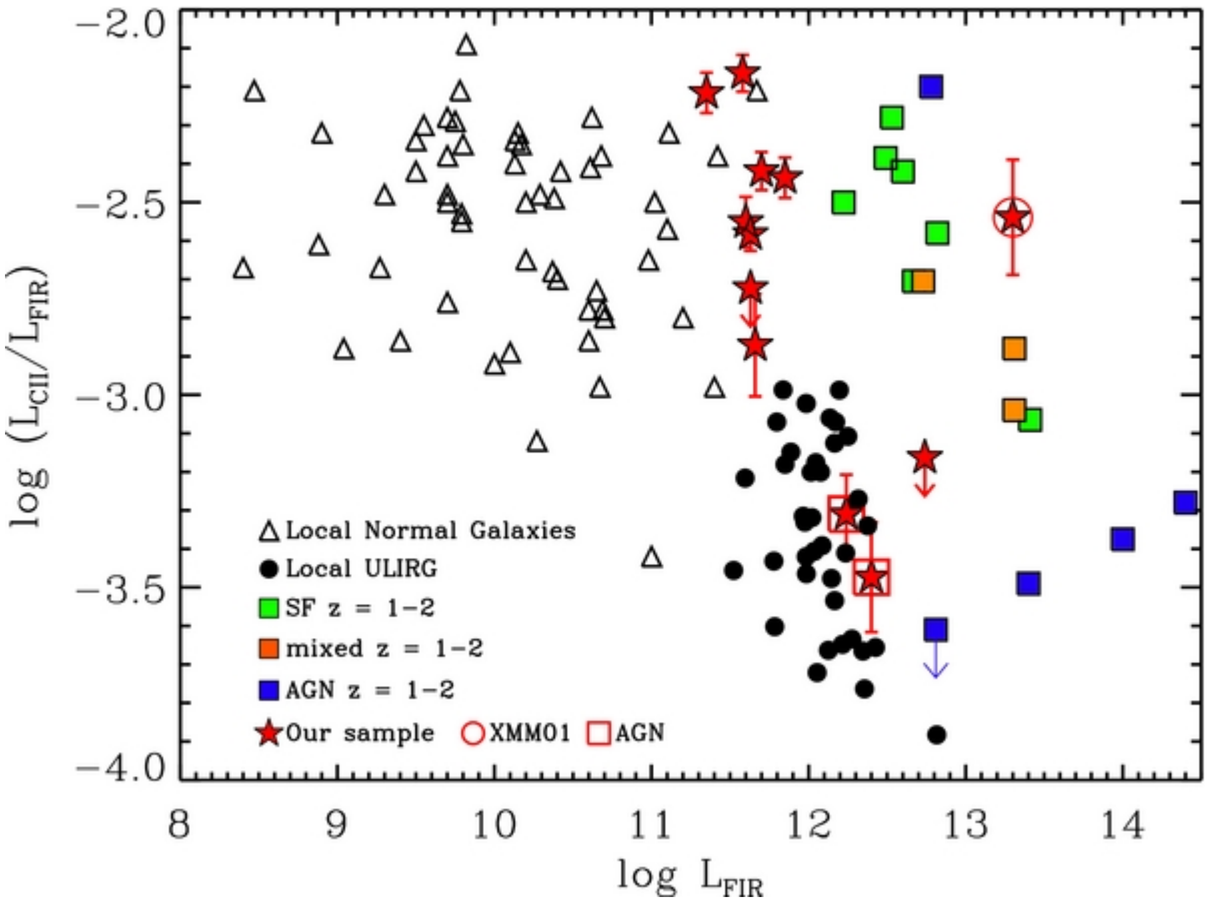
[CII] is a powerful tracer of the star formation rate in normal galaxies.



Pineda et al. 2014 A&A 570, A121

The relationship between [CII] and FIR in ULIRGS and AGNs

- FIR from dust also measures stellar energy input to ISM
- L([C II]) α L(FIR) for normal and starburst galaxies (0.1% to 1%)
- However, luminous infrared galaxies and AGNs do not obey this relationship



Rigopoulou et al. 2015

Luhman et al (1998) – ULIRGs (see also Malhotra et al. 1997)

Why is [C II]/IR Smaller in Active Galaxies?

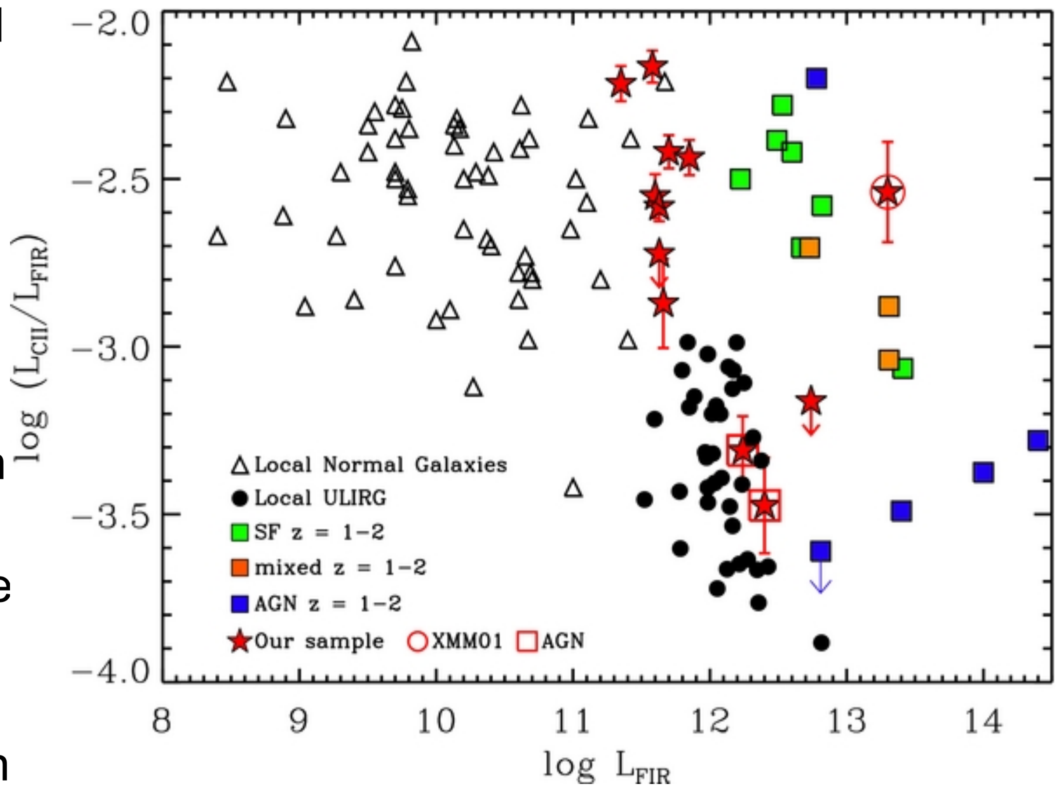
- Several Explanations – but cannot explain all observations:

- [C II] is optically thick and saturated if it arises from dense PDRs where the $^3P_{3/2}$ level is thermalized and does not radiate as efficiently as dust with increasing energy input.

- High UV fluxes produce charged grains which do not heat the gas efficiently via photoelectron ejection

- A soft UV radiation field reduces the thickness of the C^+ layer

- X-rays ionize C^+ to higher ionization states (C^{2+} ,etc) and heat the dust, so [CII]/FIR is reduced (Langer & Pineda 2015).



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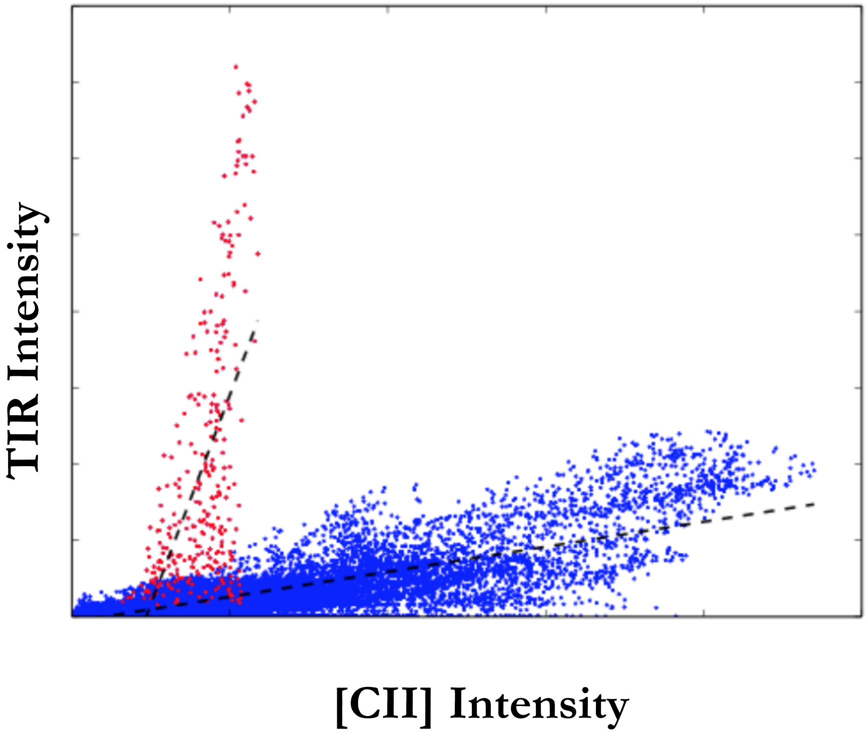
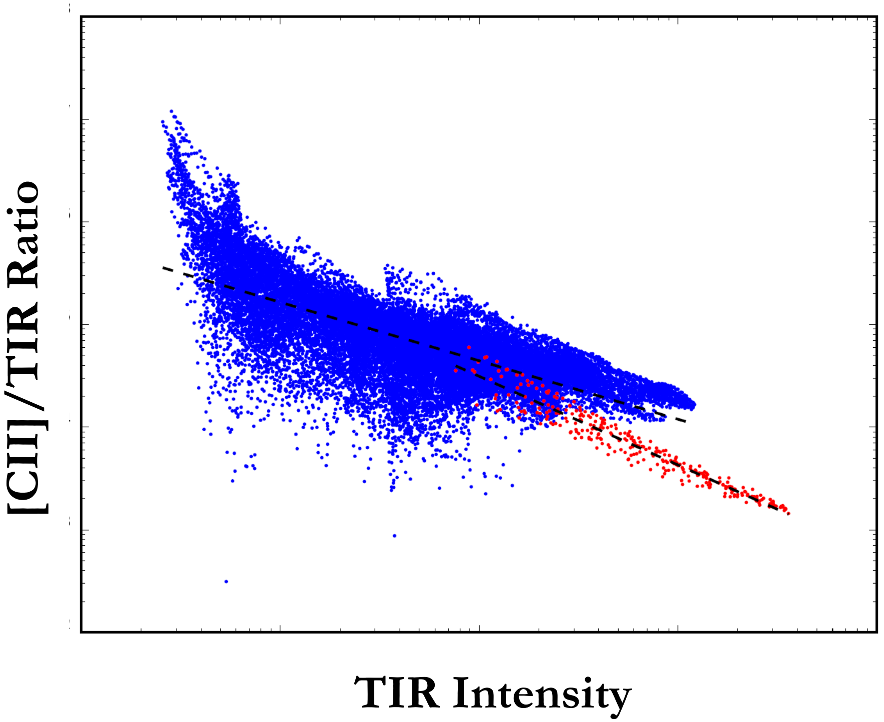
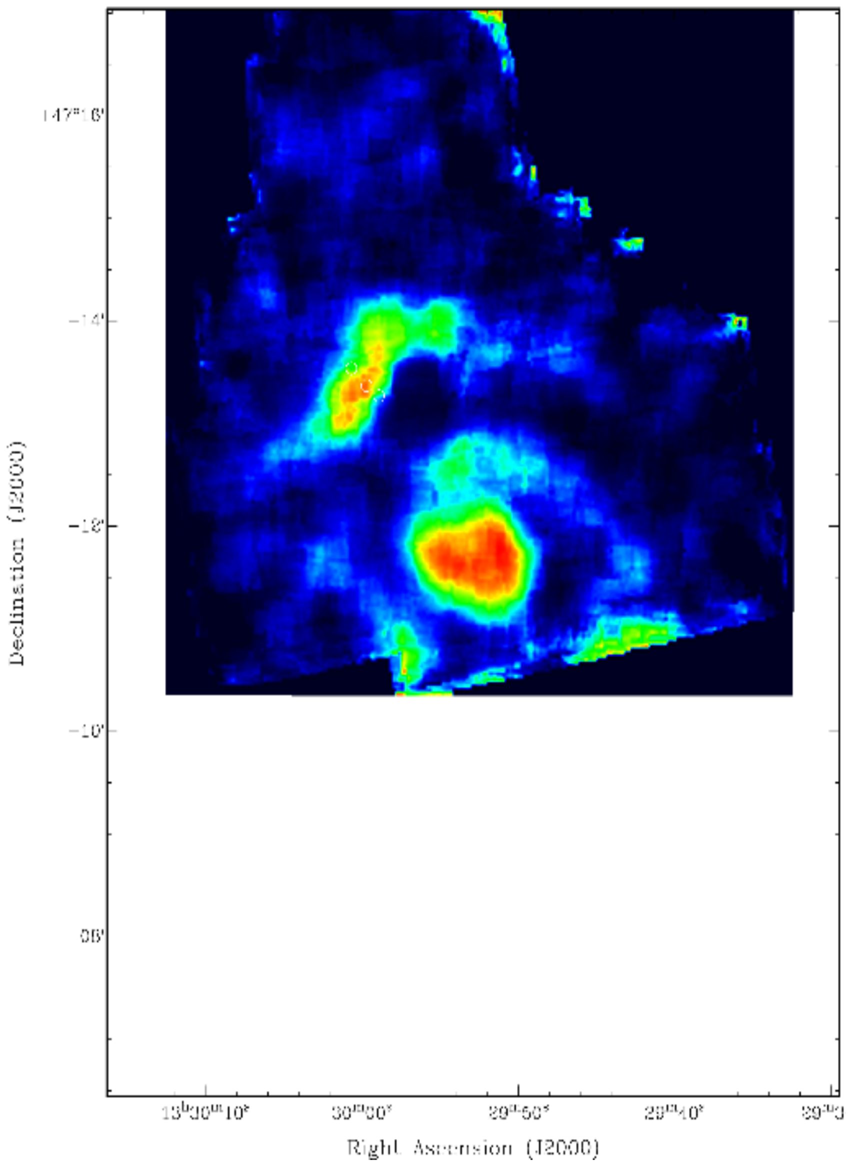
Relationship between the TIR and [CII] emission in M51





Blue Data points: M51 disk
Red Data Points: NGC5195 (The companion).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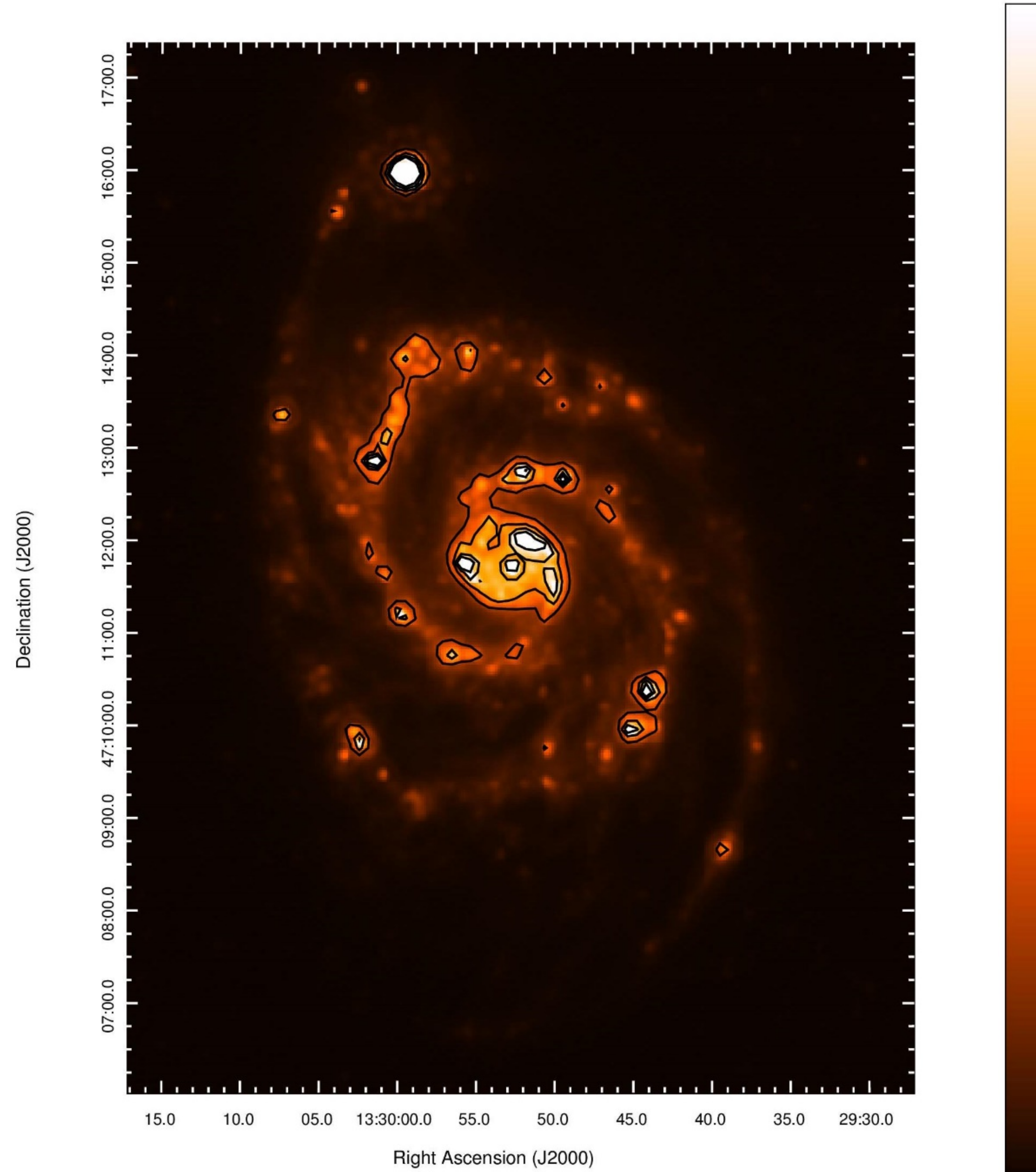
Right Ascension (J2000)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55.0
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45.0
40.0
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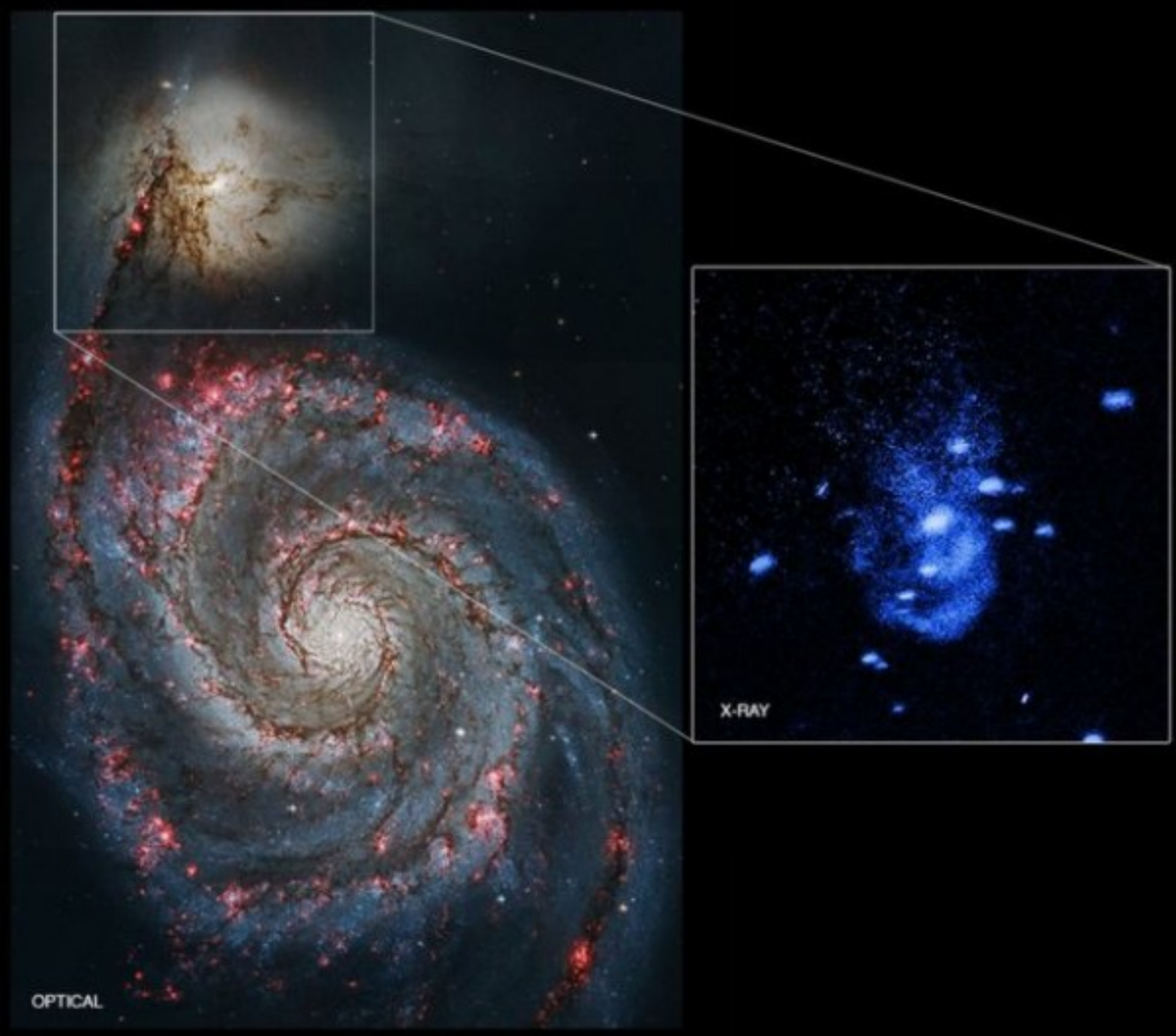
29:30.0
Right Ascension (J2000)

- The closest super massive black hole is in NGC 5195.
- X-ray emission shock arcs shows that gas is being pushed away.
- Closest example of AGN feedback.
- The lack of [CII] in the companion could be an effect of X-rays suppressing the C^+ abundance (for higher ionization levels) or that [CII] is in absorption. upGREAT observations will help us answer the latter.
- Companion might be an ideal location for studying the [CII] deficit observed in ultraluminos infrared galaxies.



Schlegel et al. 2016

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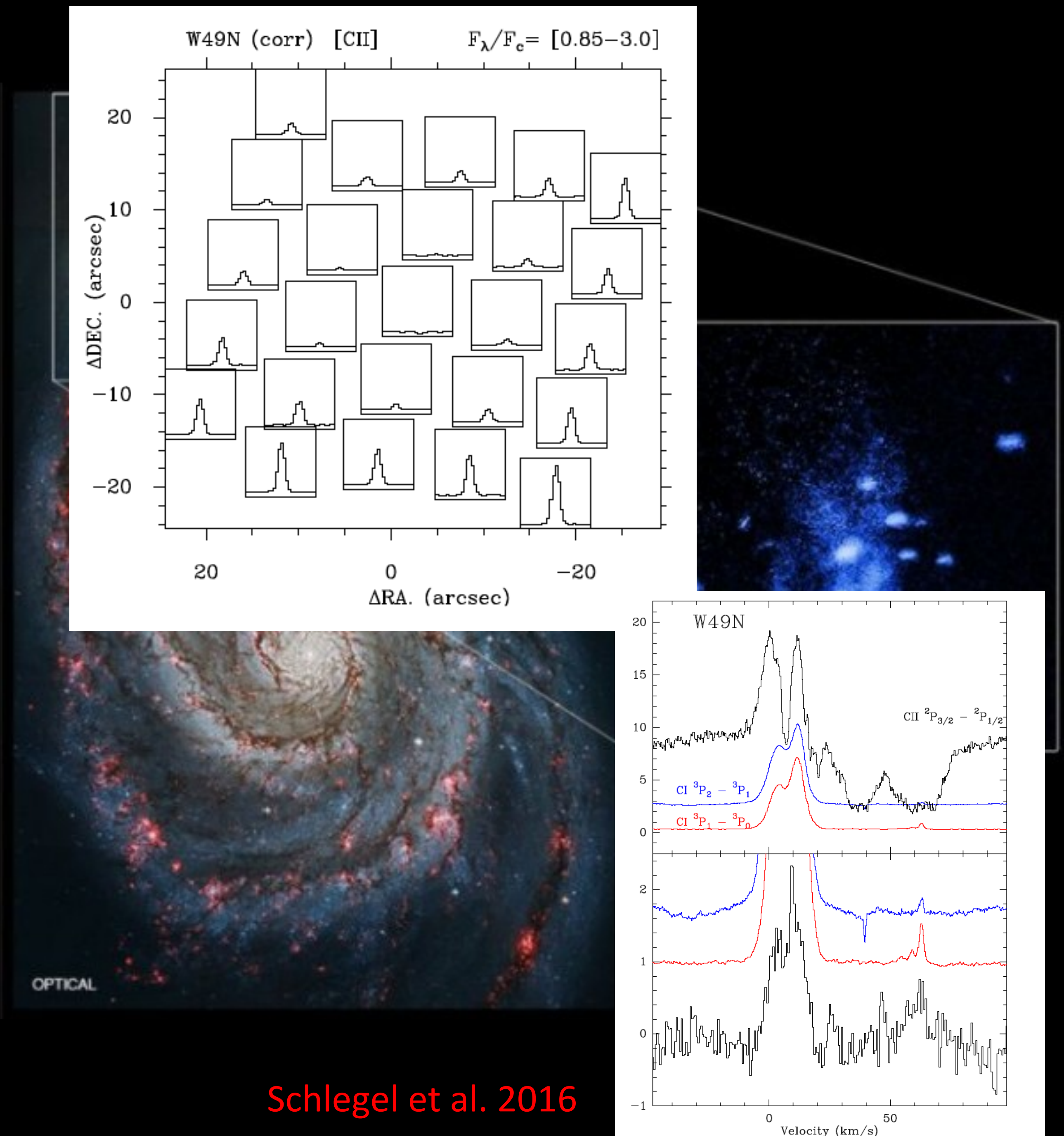
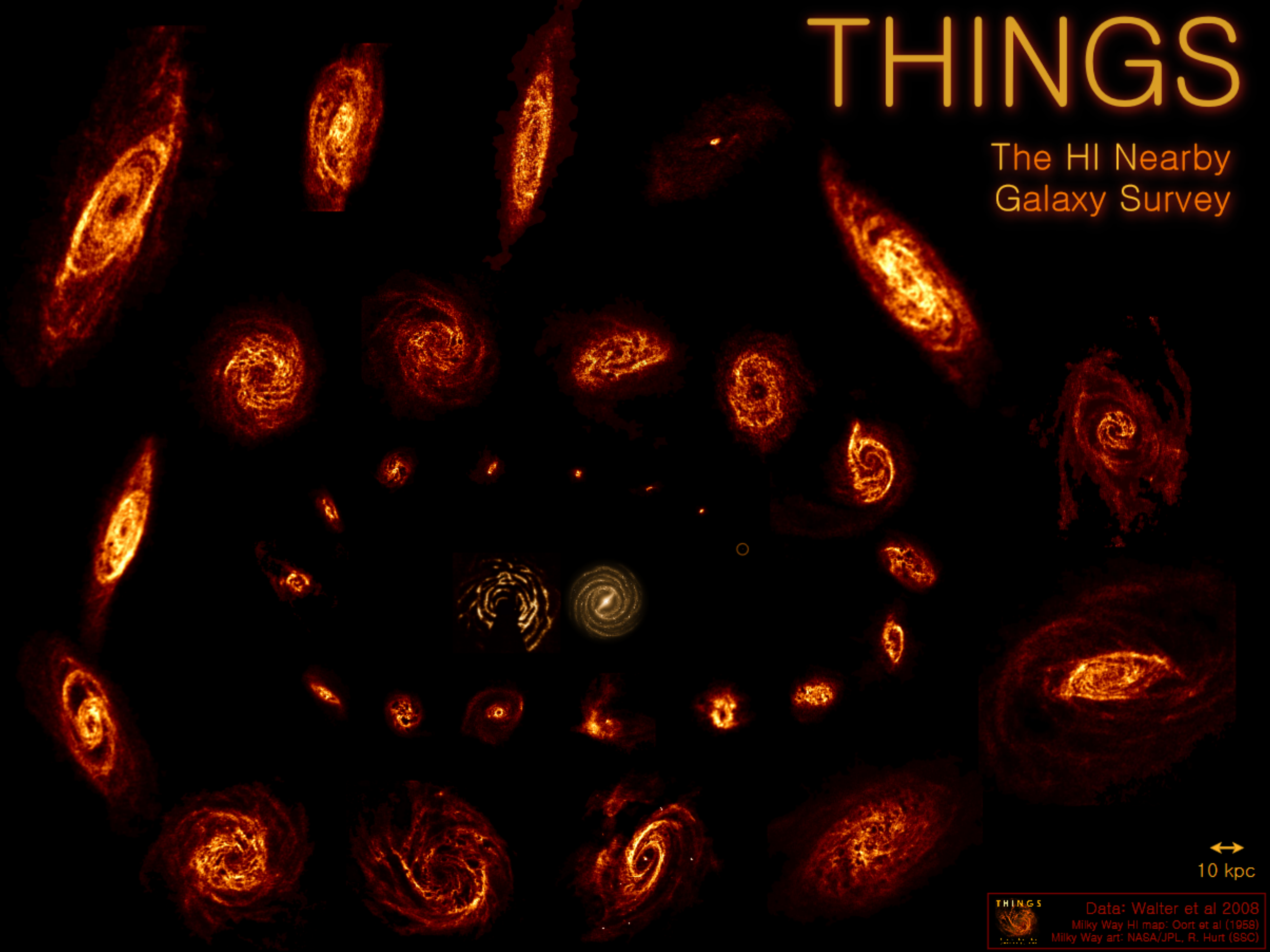
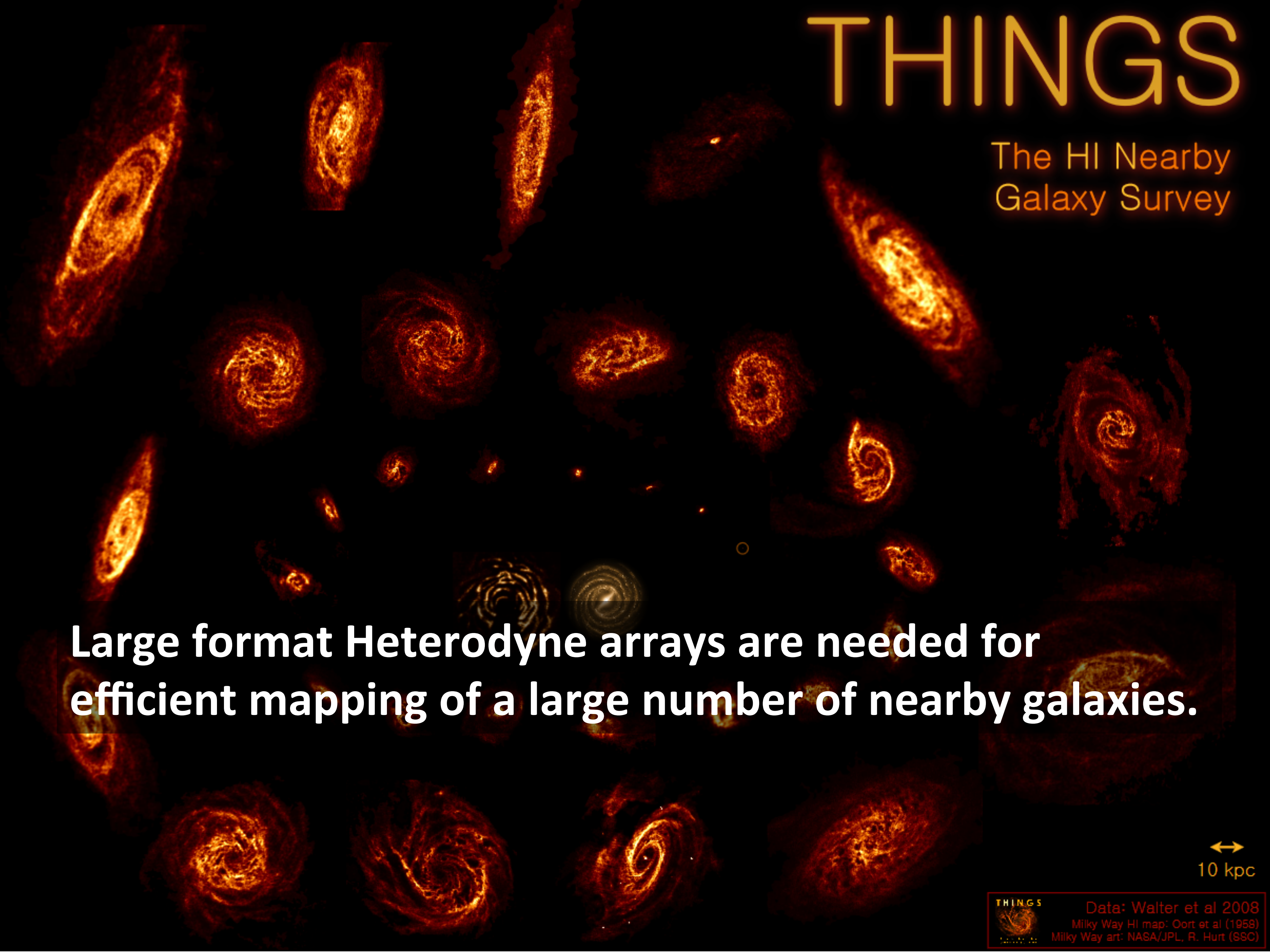


Schlegel et al. 2016


THINGS
The HI Nearby
Galaxy Survey
10 kpc
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)



Large format Heterodyne arrays are needed for efficient mapping of a large number of nearby galaxies.

Conclusions

- We will have a complete map of all constituents of the ISM in the M51 grand design galaxy and its companion.
- We will study the interaction of the spiral density waves with the ISM of M51 and will study how it influences the formation of stars.
- We clearly see the stratification of different ISM components in space and in velocity.
- [CII] is well correlated with SFR in the disk of M51, but not in the companion.
- First publications mid-2017, in time for senior review.