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

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Motivation: Regulation of Star Formation in Galaxies

- Star formation is an inefficient process in which only a few percent of the interstellar mass is converted into stars.

- While in massive galaxies star formation is possibly suppressed by their AGN, galaxies like the Milky Way are mostly regulated by stellar feedback.

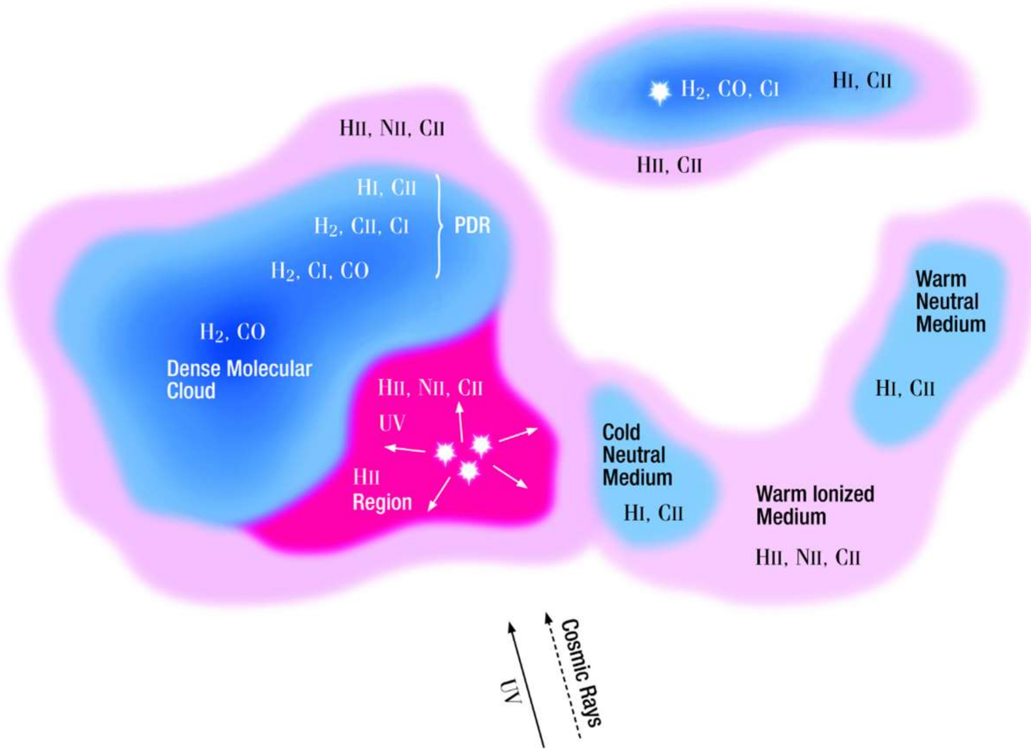
- In nearby star forming regions, small scale stellar feedback processes can be studied in detail.

- But we need to go to external galaxies to study processes at large scale, such as super bubbles, bars, and spiral arms.

- These processes are responsible for putting the gas together for star formation.

The [CII] 158um Line

- Carbon is the fourth most abundance chemical element in the universe.
- The C+ ion has one fine-structure transition at 158um.
- Carbon is singly ionized (C^+) in environments illuminated with far-ultraviolet radiation from massive stars.
- It is excited by collisions with e^-, H, and H_2, and therefore the [CII] line is a tracer of ionized gas regions, neutral atomic clouds, and diffuse molecular clouds (CO-dark H_2 clouds).

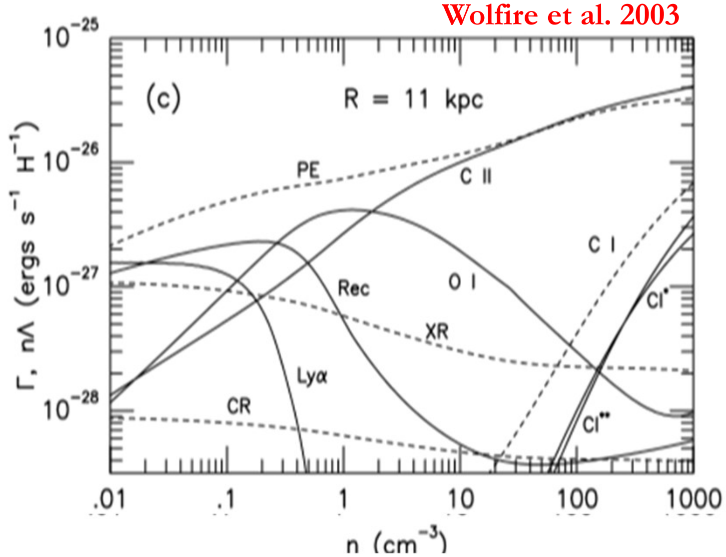


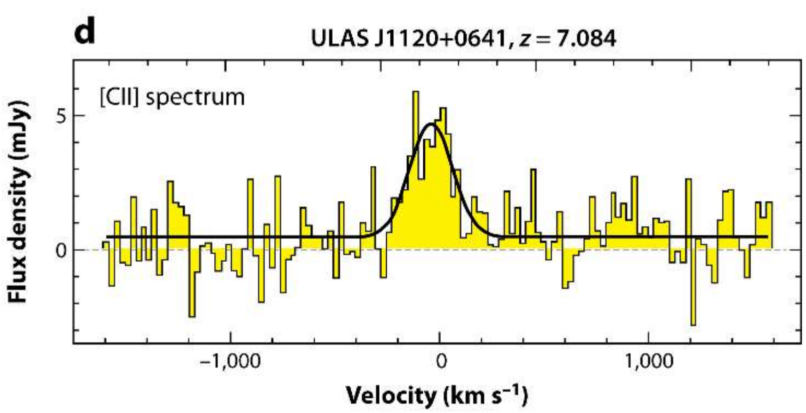
Photon-dominated region (PDR): Region where the chemistry and thermal balance is dominated by the far-ultraviolet radiation field from massive stars.

The [CII] 158um Line

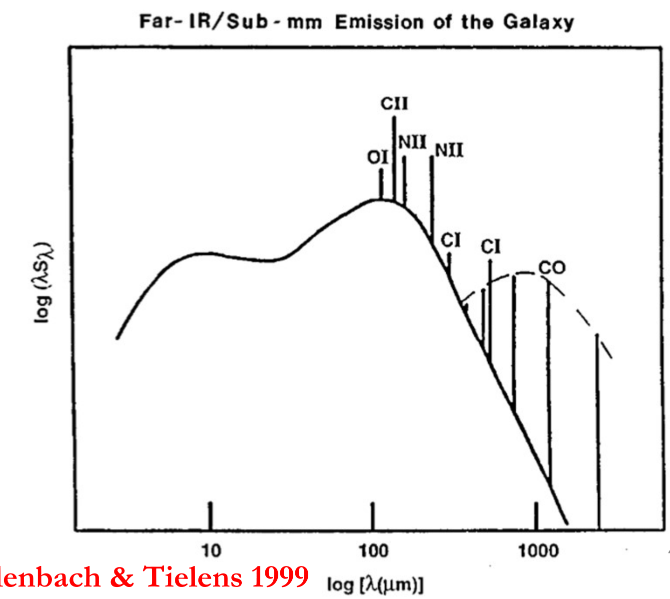
- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM.
- It represents 0.1 to 1% of the total far-infrared continuum, and it is the brightest FIR line.
- Thus, the CII line is a tracer of star formation in galaxies.

Wolfire et al. 2003





Wang et al. 2013 ApJ 773, 44

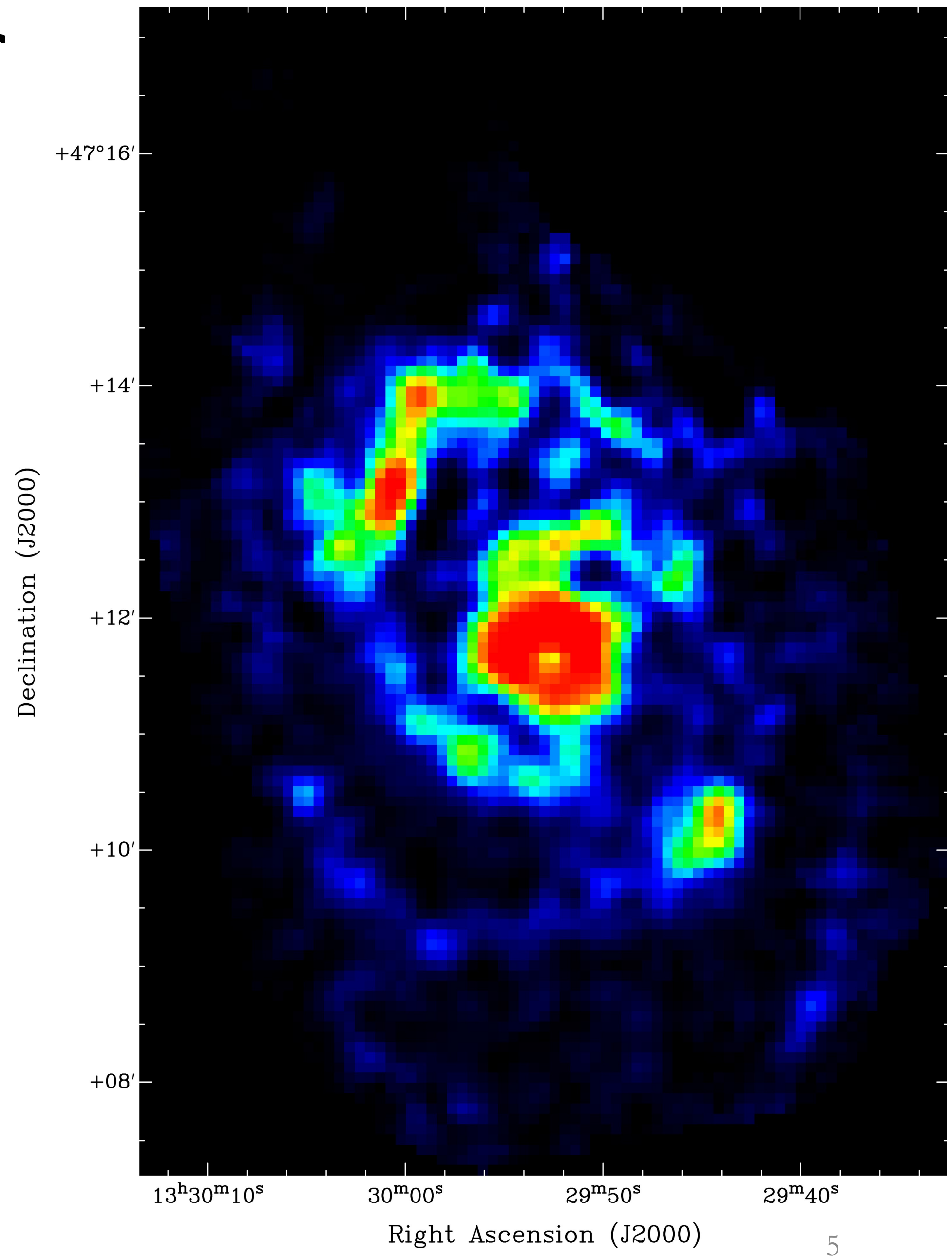


Hollenbach & Tielens 1999

The SOFIA [CII] Map of M51

- Joint impact project between US and German institutions.
- 75h of observing time over several SOFIA Cycles.
- 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.

upGREAT Map of M51

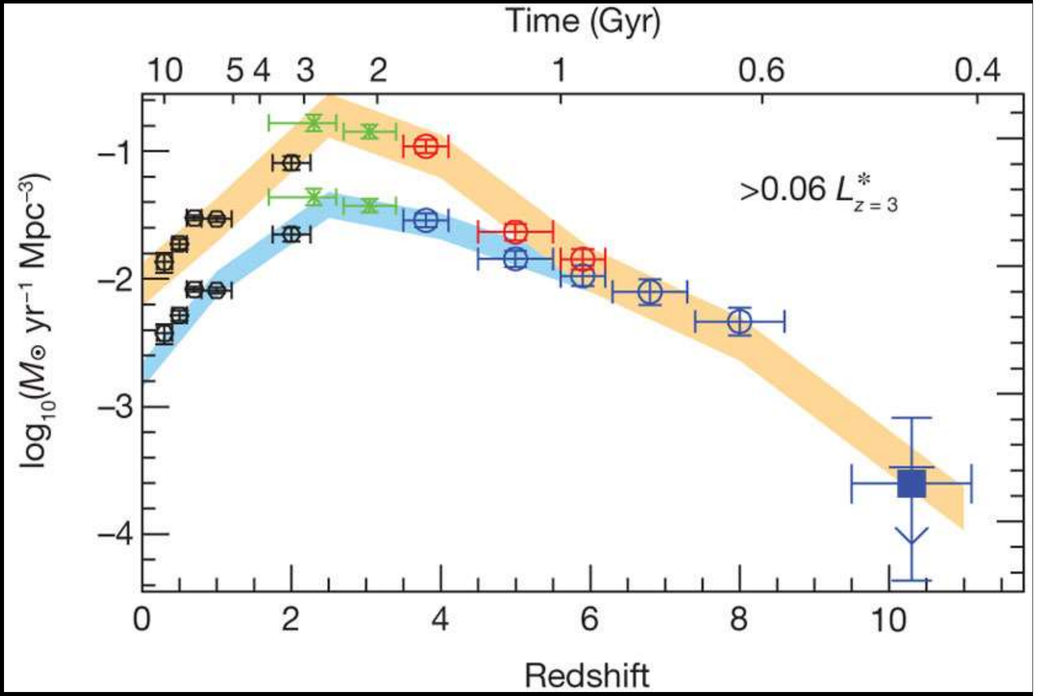


SOFIA [CII] Mapping of M51: Science Goals

- 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 star formation rate

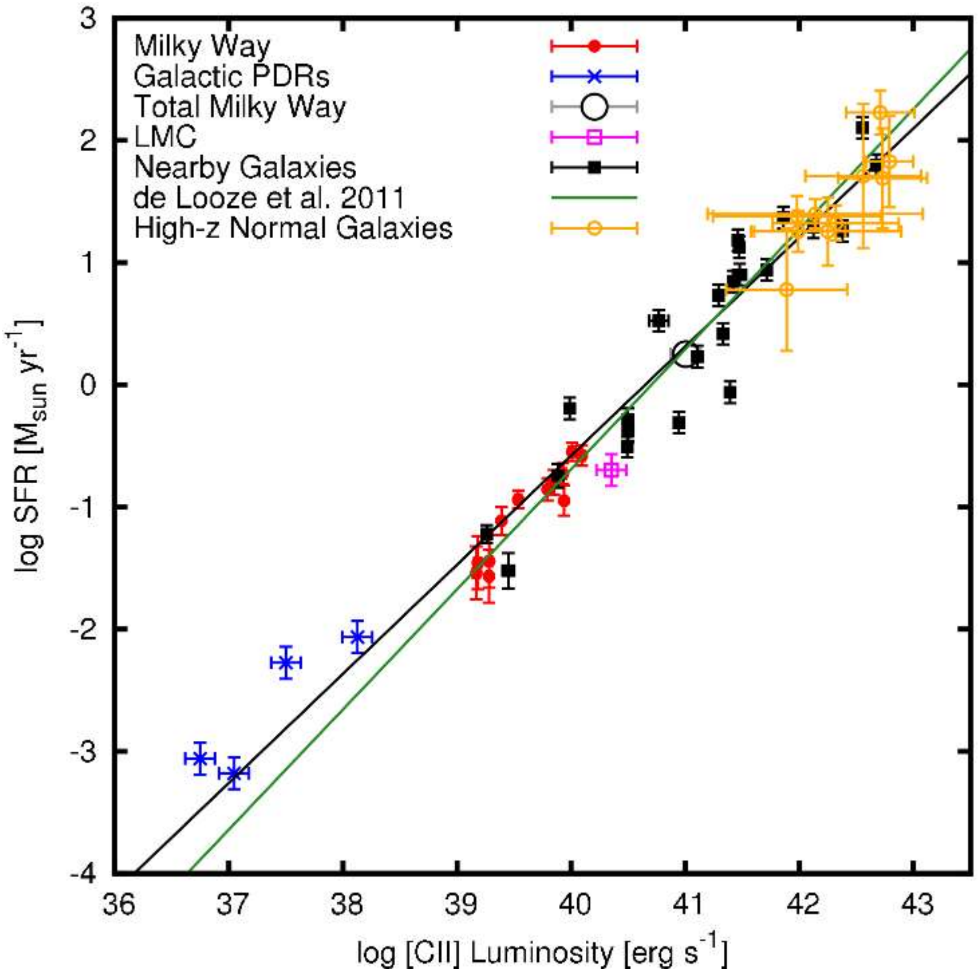
- An important parameter used to characterize star formation in galaxies over cosmic time.
- The peak of star formation in the Universe occurred at redshift Z=2.
- It is important to find tracers of star formation that can be observed in galaxies over a wide range of redshifts.



The [CII] 158um Line

- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM. So, it should trace star formation.

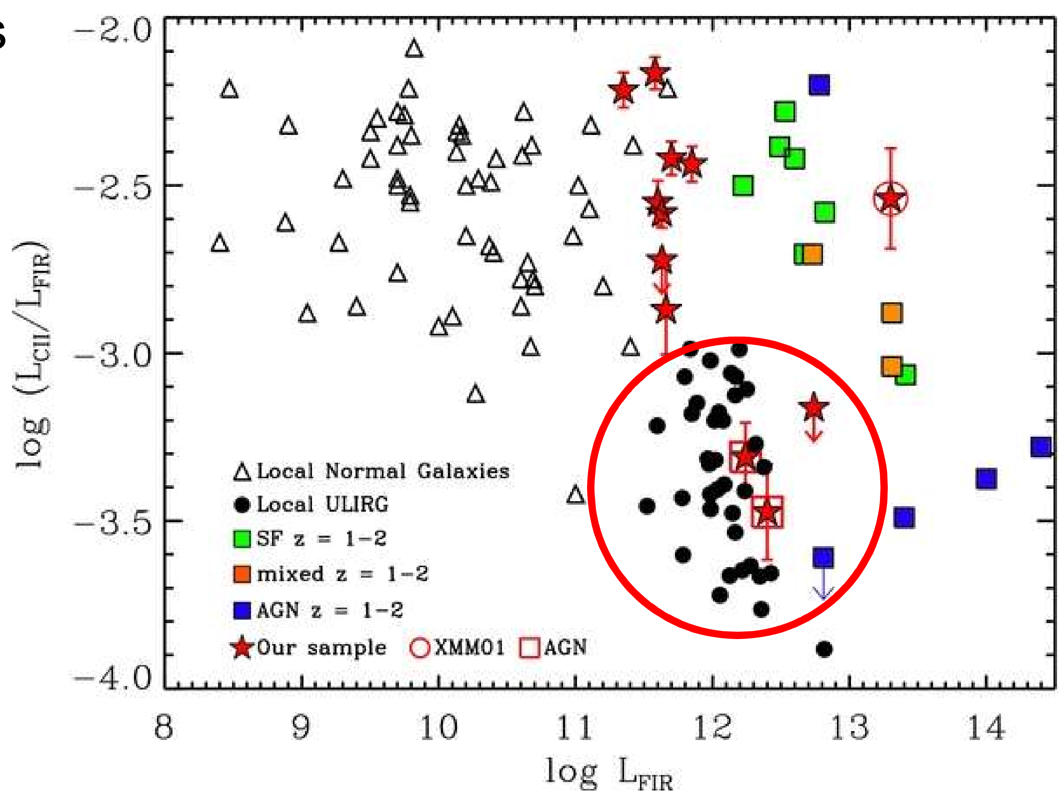
- The [CII]-SFR correlation extended over several orders of magnitudes in these quantities.



Pineda et al. 2014 A&A 570, A121

The [CII] 158um Line

- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM.
- But a [CII]/FIR deficit is observed in ultra luminous infrared galaxies.



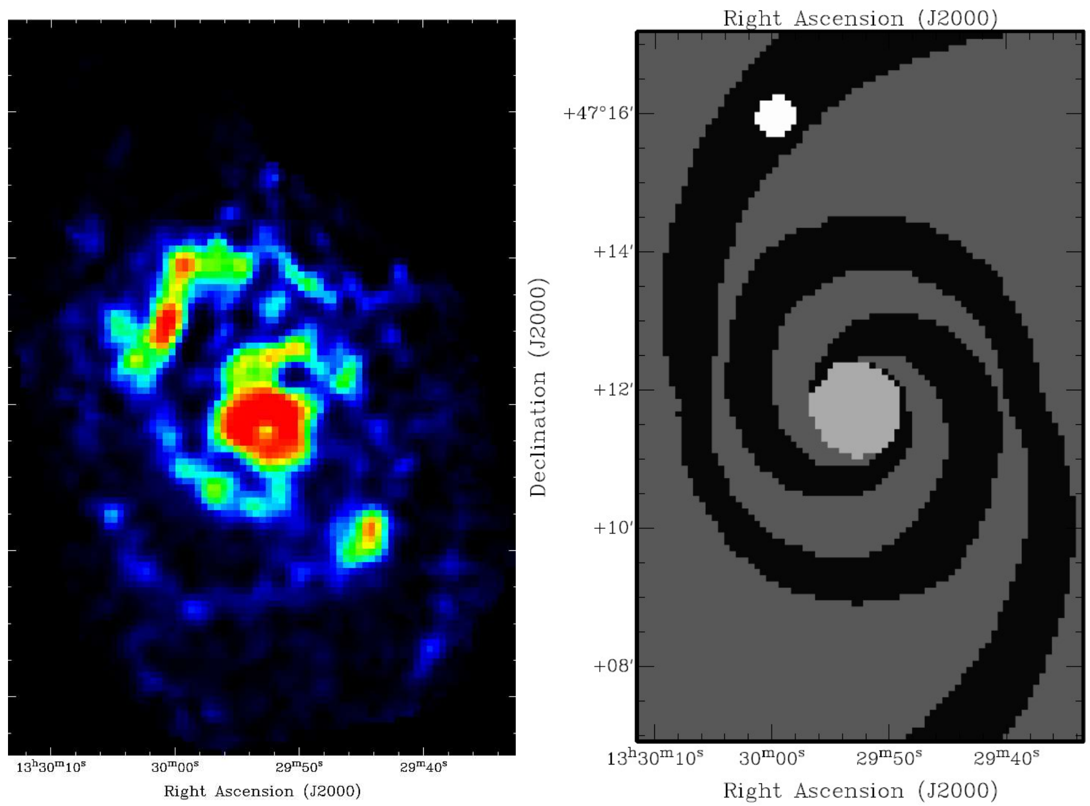
Rigopoulou et al. 2015

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

[CII] as a tracer of star formation over different environments in M51

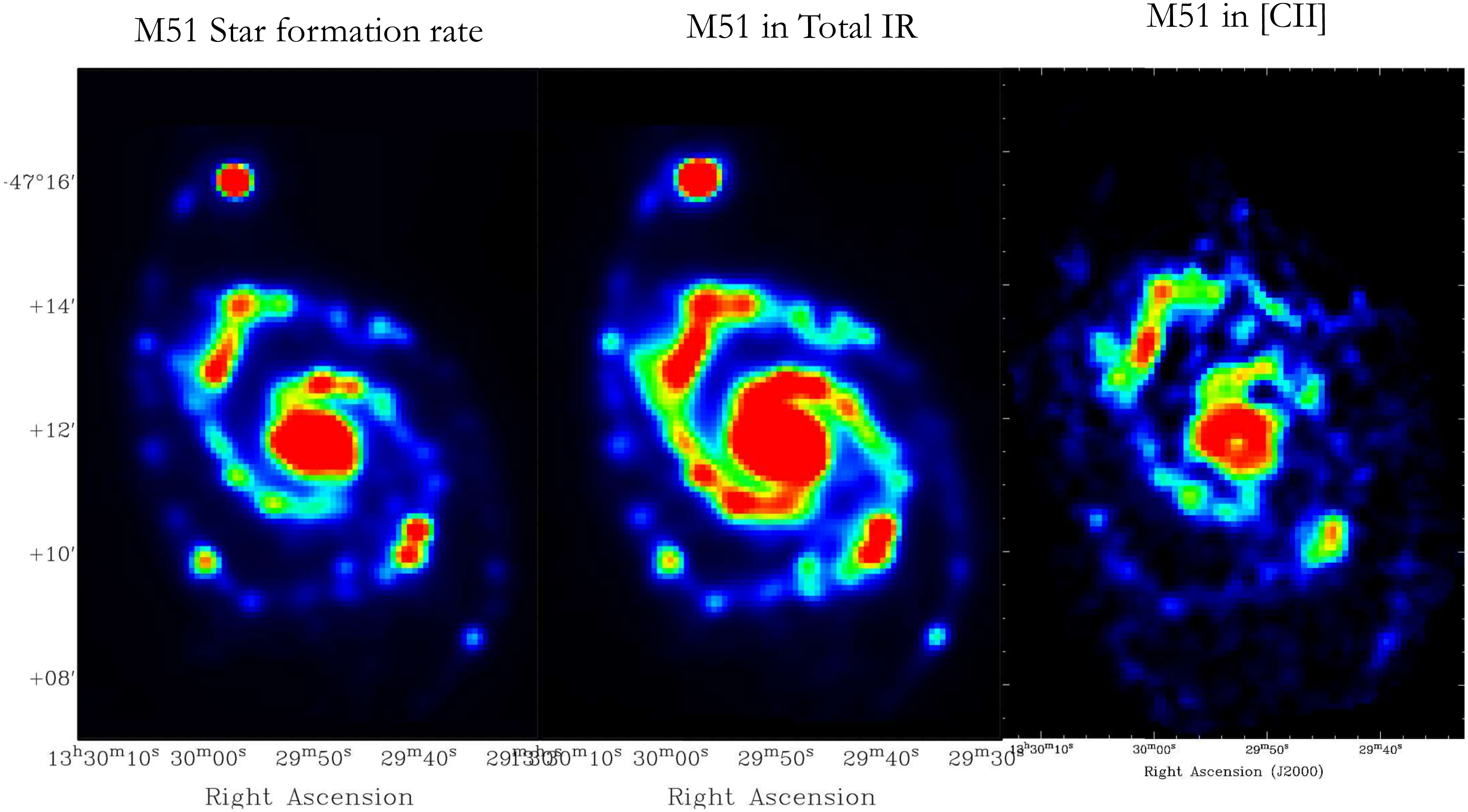
M51 in [CII]

- A complete [CII] map in M51 allow us to study its relationship with star formation over a wide range of environments.
- We defined four environments: M51's center, Spiral arms, inter-arm regions, and M51b.
- We compared the FIFI-LS [CII] map with:
  - SFR=Ha+24um (unobscured+obscured star formation)
  - TIR (total infrared) = I(8um)+I(24um)+I(70um)+ I(160um)



Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

[CII] as a tracer of star formation over different environments in M51

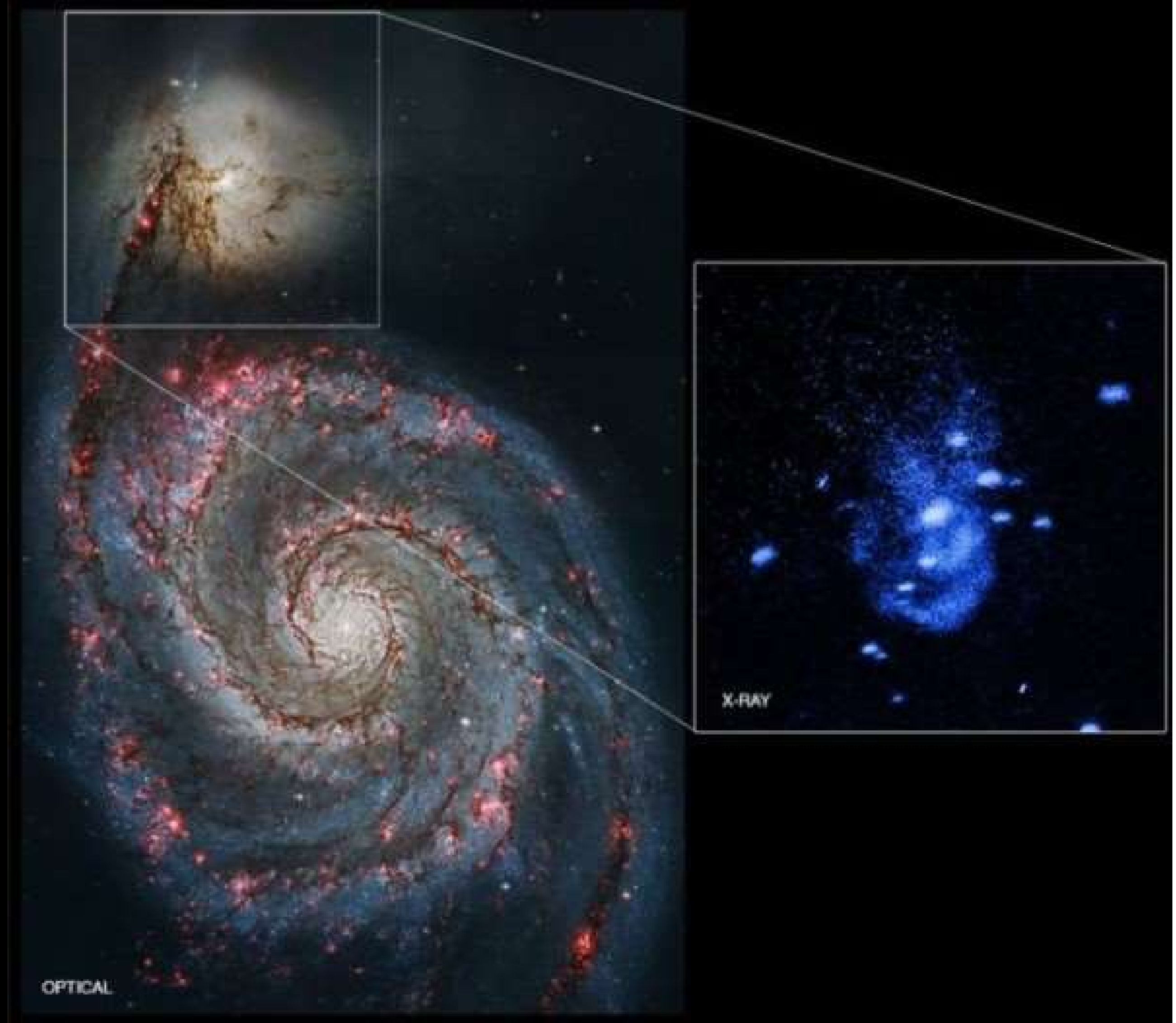


SFR=Ha+24um

Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

M51b

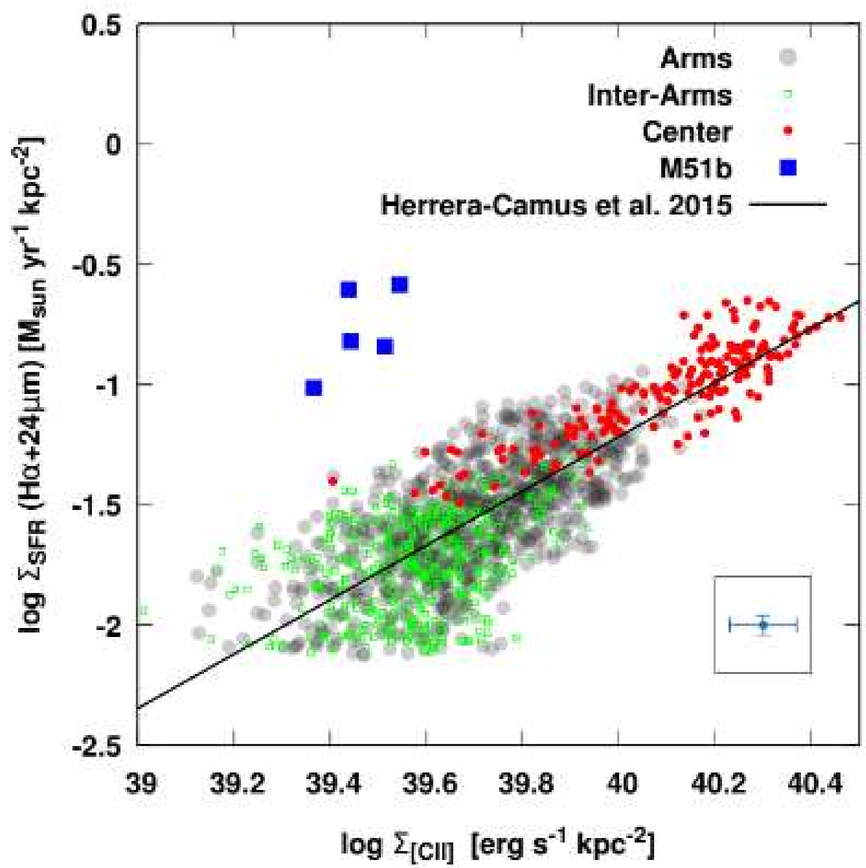
- The closest super massive black hole is in NGC 5195.
- X-ray emission shock arcs shows that gas is being pushed away.
- Closest example of AGN feedback.



Schlegel et al. 2016

[CII] as a tracer of star formation over different environments in M51

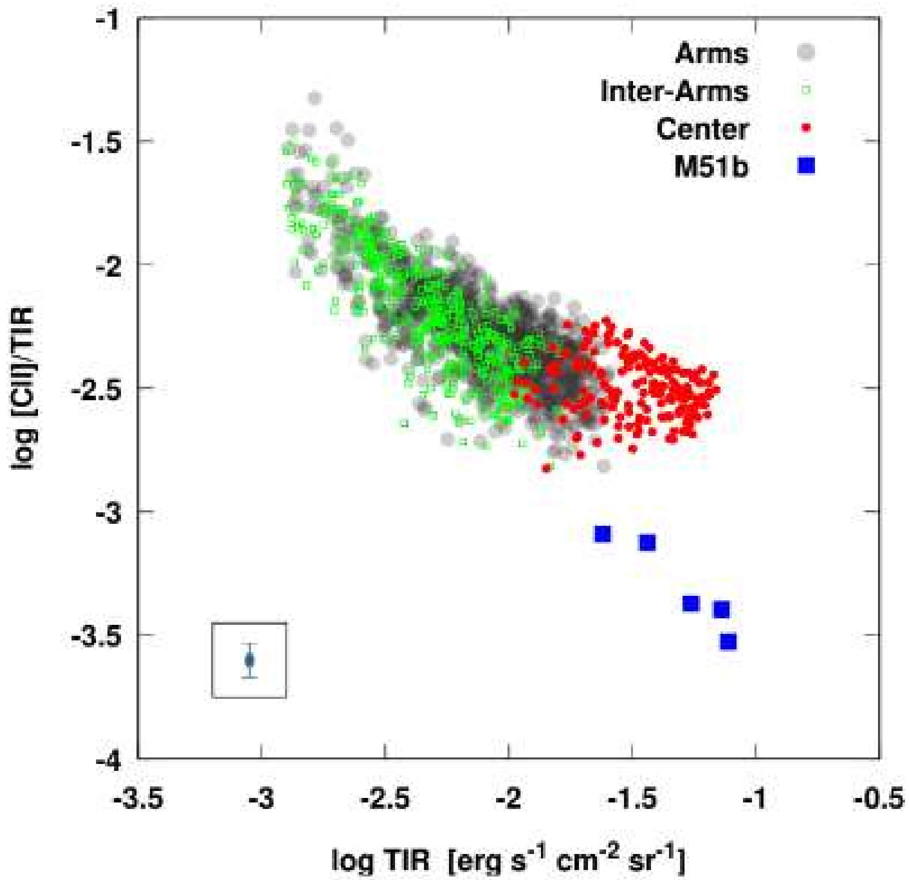
- [CII] and the SFR are well correlated in the disk of M51 (arms, inter-arms, and galactic center).
- The [CII]-SFR relationship is similar to that in the Milky Way and other nearby galaxies (black straight line is fit to *Herschel*/KINGFISH galaxies).
- But the companion galaxy, NGC5195 shows a deficit of [CII] with respect to FIR emission.
- SFR and TIR intensities are dominated by 24um emission in M51b.



Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

[CII] as a tracer of star formation over different environments in M51

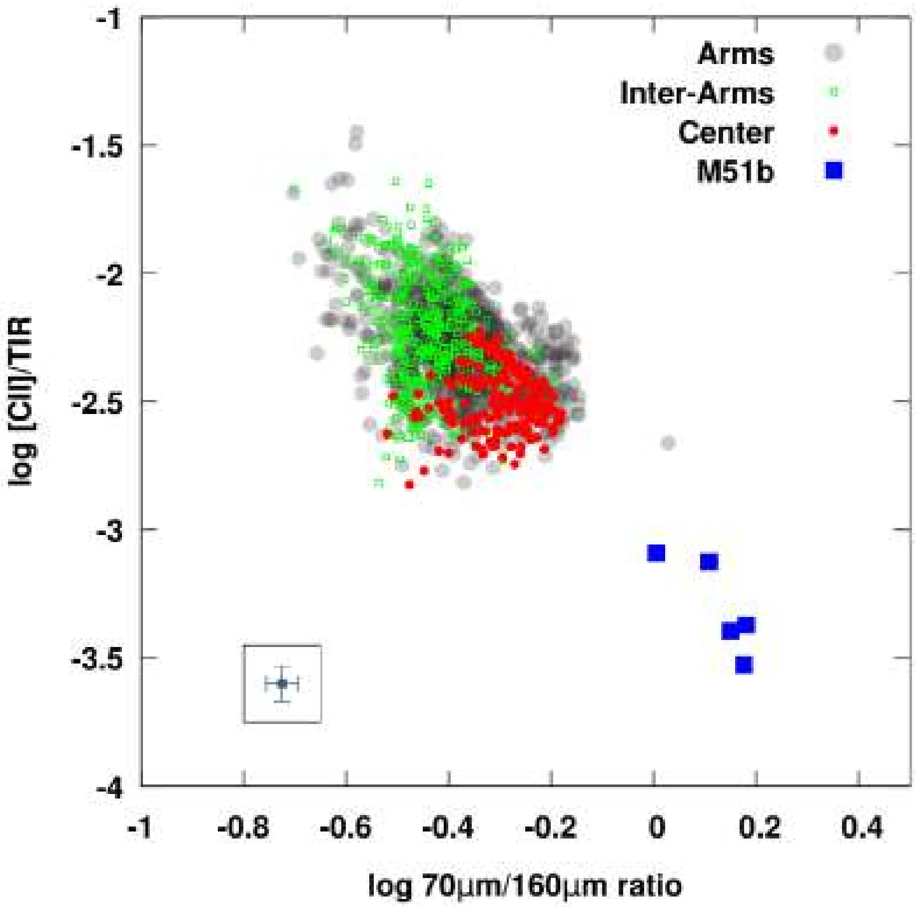
- The disk of M51 has a [CII]/TIR ratio that is typical of normal galaxies (10^{-3}-10^{-2}).
- But companion galaxy shows much lower [CII]/TIR ratios.
- Such low values are typical of ULIRGs (Diaz-Santos 2014).
- But note that the TIR luminosity is at least two orders of magnitude lower than those in ULIRGs.



Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

[CII] as a tracer of star formation over different environments in M51

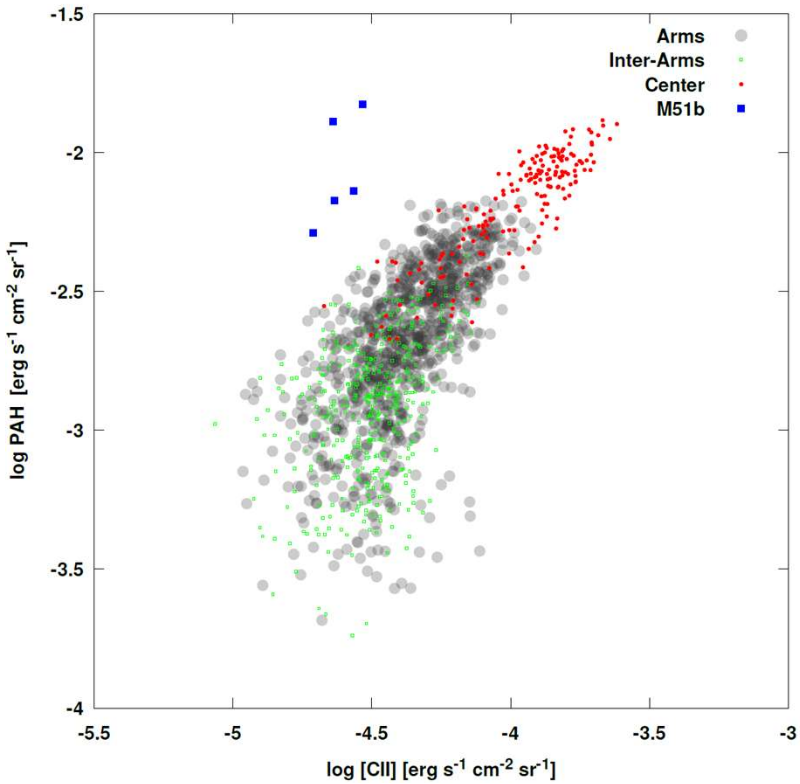
- When comparing the [CII]/TIR ratio with the 70um/160um ratio, we find that the galaxy center is higher than spiral arms and inter-arm regions.
- The 70um/160um ratio is a proxy for dust temperature.
- But, again, M51b, has enhanced 70um/160um ratio.
- Dust in M51b is hotter than in the disk of M51.



Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

[CII] is also in deficit with respect to PAH emission

- PAH/VSG are expected to dominate the photo-electric heating form massive stars which is later radiated in [CII].
- There is bright PAH emission from a compact source associated with the AGN in M51b.
- There is still a deficit of [CII] emission with respect to the PAH intensity.
- Note that AGNs can also power PAH emission in their close vicinity (e.g. Jensen et al. 2017 MNRAS 470,3071).



PAH emission derived from 8um emission with a stellar contribution correction that uses the 3.6um images. (Croxall et al. 2017)

Origin of [CII] deficit in M51b?

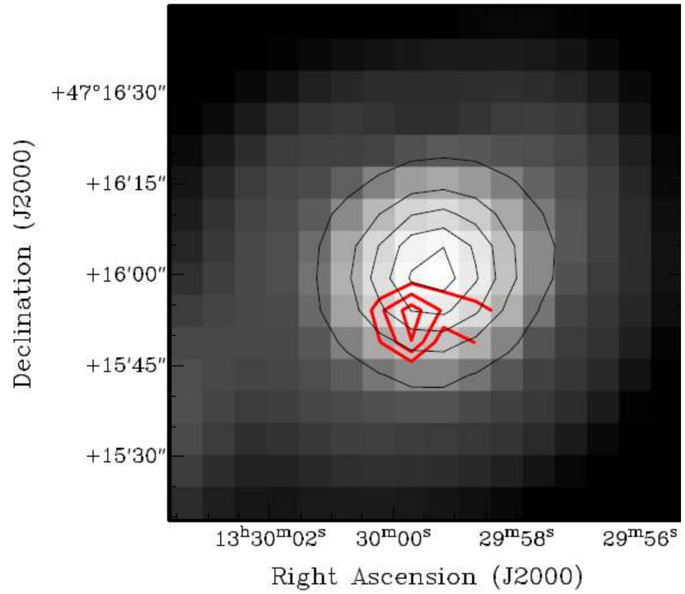
- Faint [CII] is detected in the S—W part of the galaxy.
- Stacked upGREAT spectra in this region show emission at a velocity that is consistent with that of CO in the S-W part of M51b. CII] is likely detected in the disk of M51b.

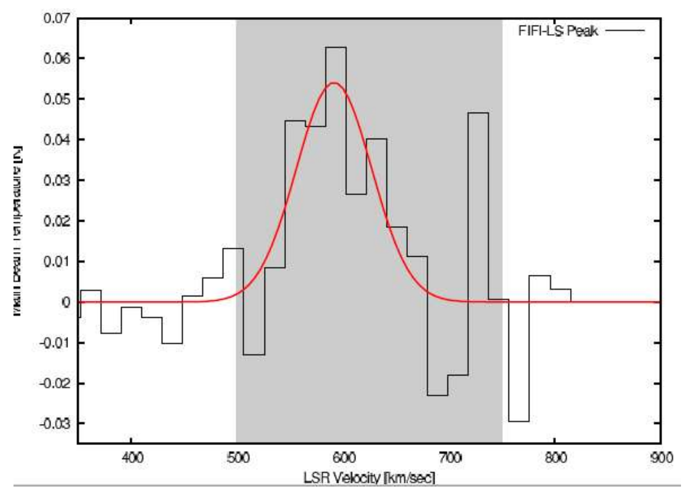
- Bright Far and Mid- infrared emission arises from location of black hole, but no [CII] counterpart detected.

- X-rays from the AGN might be responsible for heating the Far- and Mid- infrared emission. But this process is not very efficient and M51b is a relatively faint X-ray source.
- PAHs are also bright near the AGN, so there should be plenty of ISM heating there.

- Higher spatial resolution mid-IR observations are needed for resolving sources of emission (EXES?).

- ***M51b is an important nearby laboratory to study the deficit of [CII] emission in galactic nuclei.***





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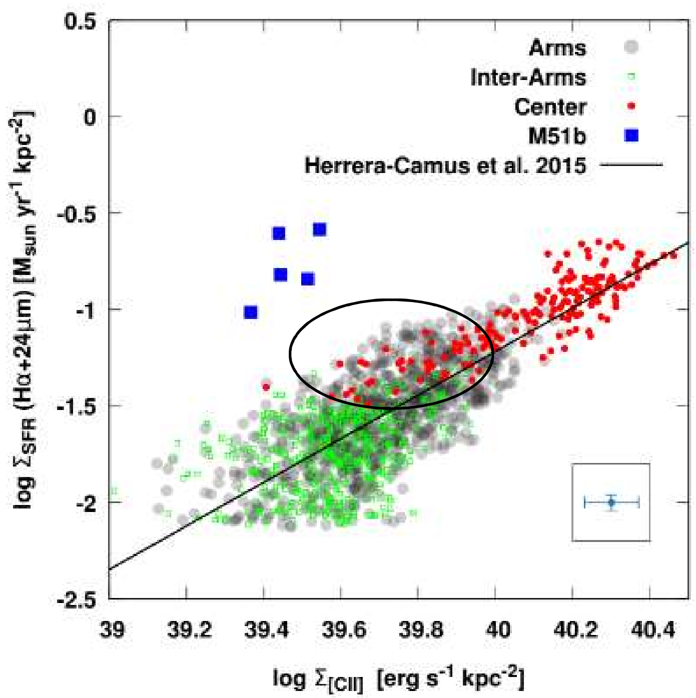
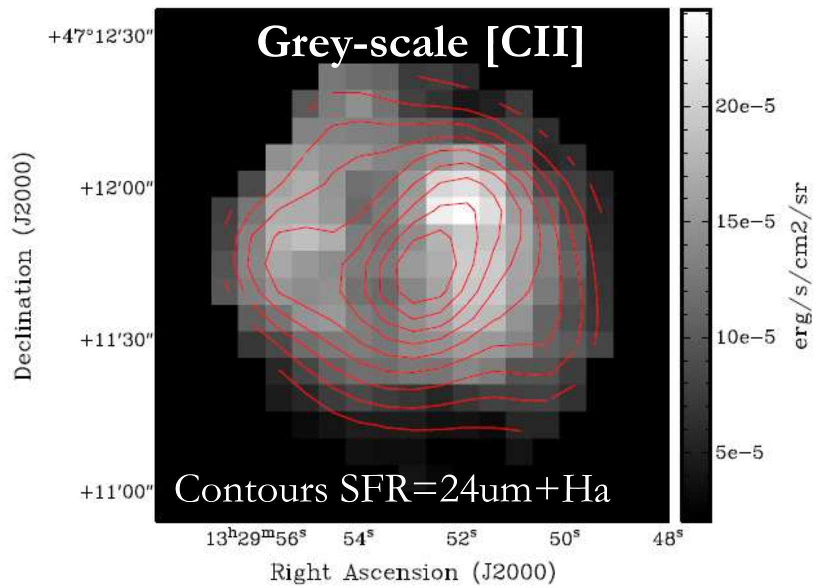
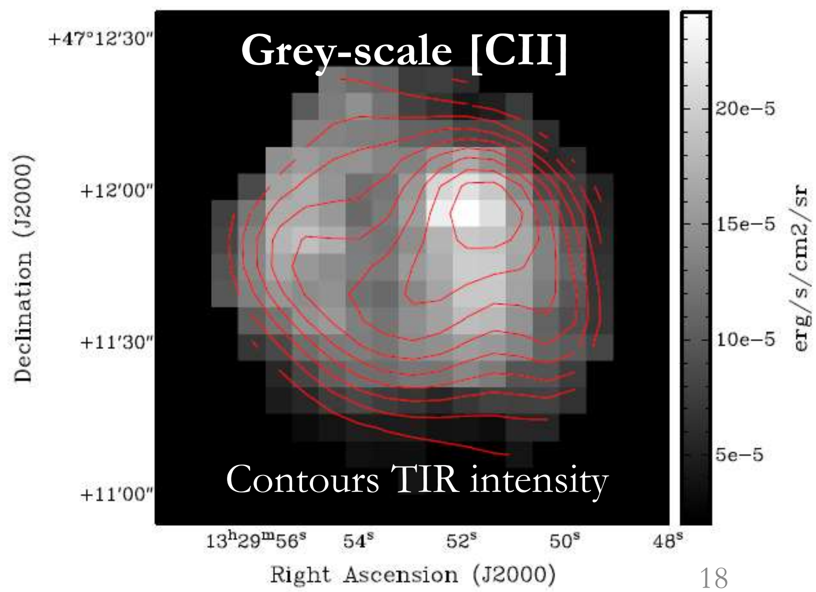
Some deficit is seen in M51's center.

- In M51's center FIR intensity follows the distribution of [CII] but for the SFR (dominated by 24um) there is also a suggestion of a [CII] deficit.

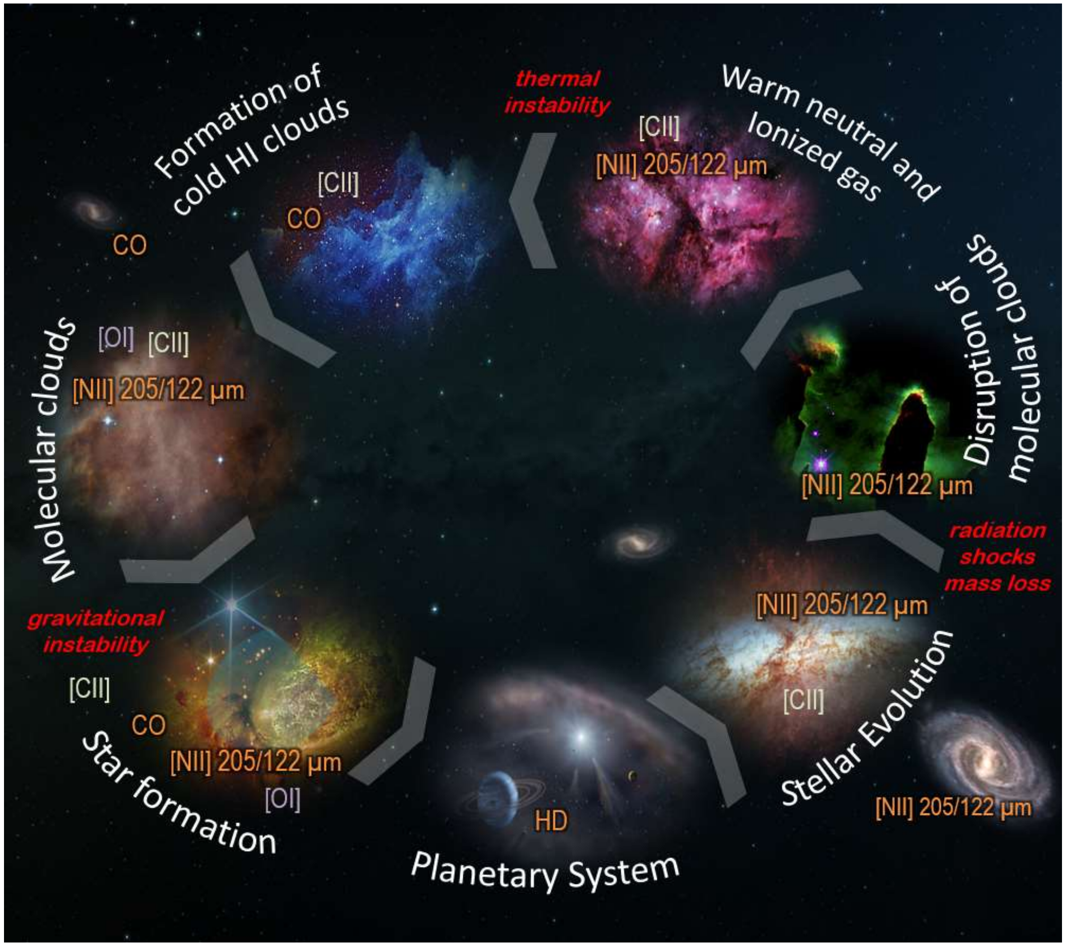




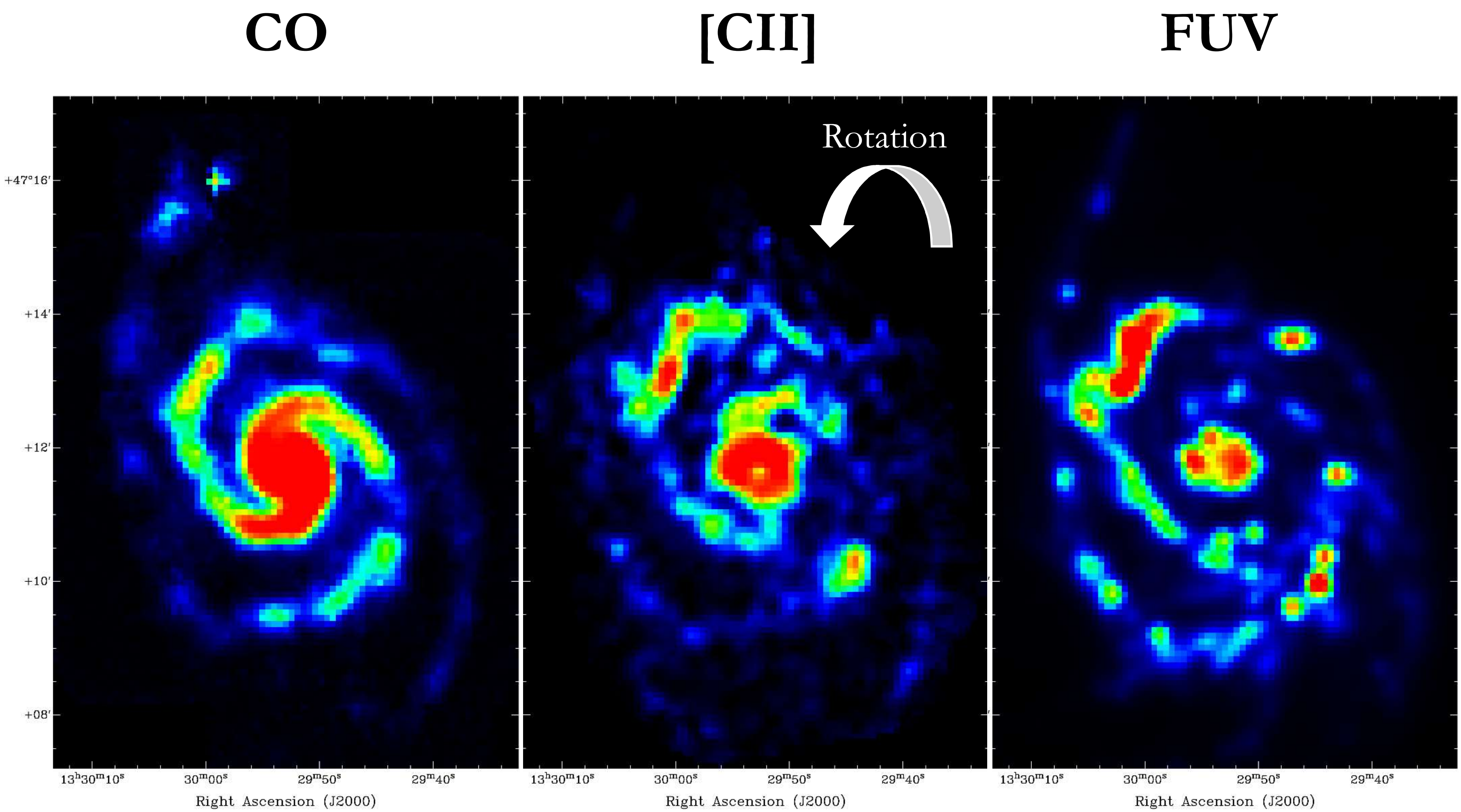


Impact of spiral density waves on the evolution of the ISM and star formation

- Spiral density waves play a fundamental role in compressing gas, making it available for star formations.
- Dense molecular gas can be traced by CO emission.
- Obscured star formation activity can be traced by [CII].
- When massive stars disrupt their progenitor material, FUV photons can scape, and they can be traced by FUV emission.



Impact of spiral density waves on the evolution of the ISM and star formation

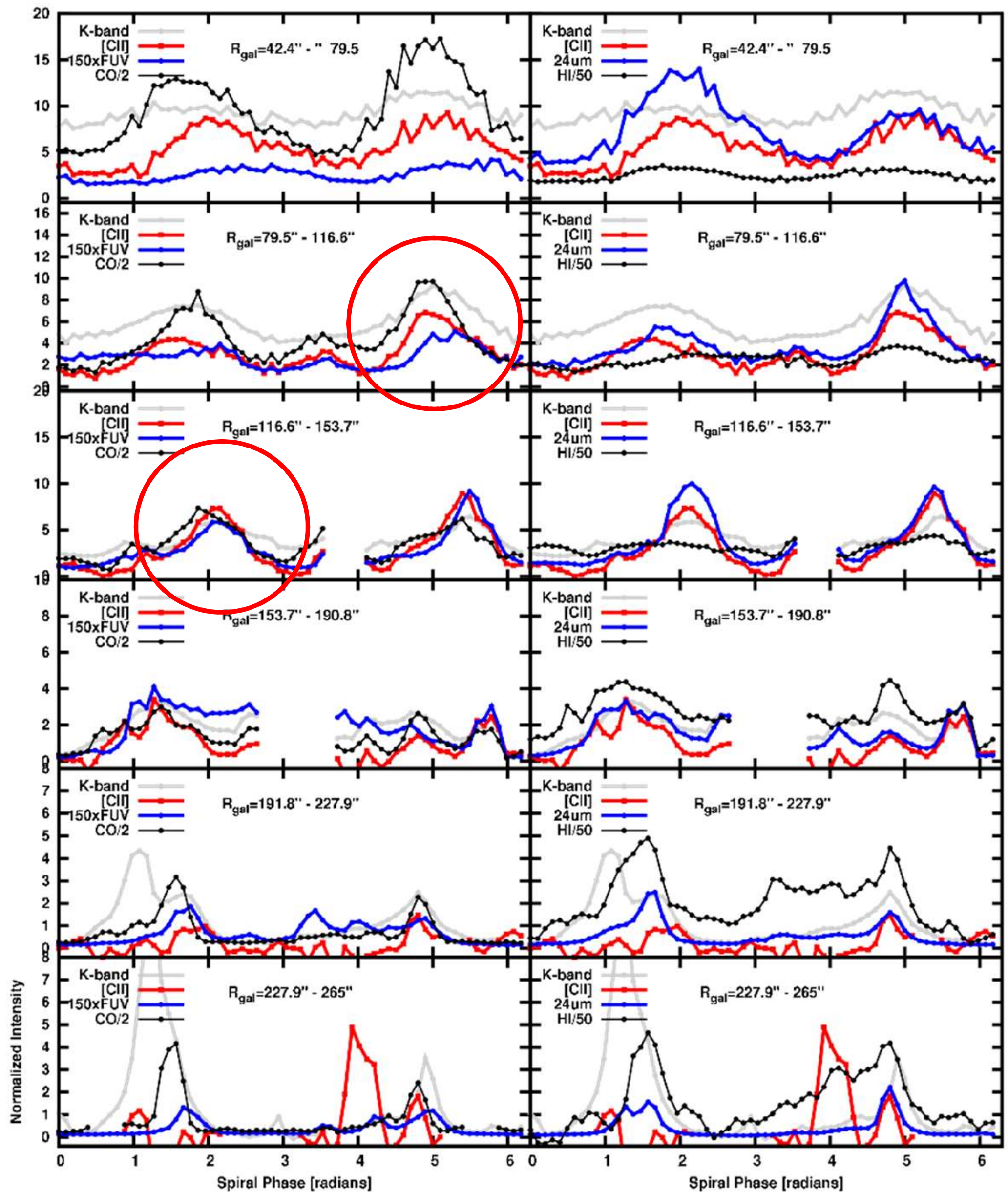


- **Molecular clouds (CO) -> Star formation ([CII]) -> cloud dispersion (FUV).**

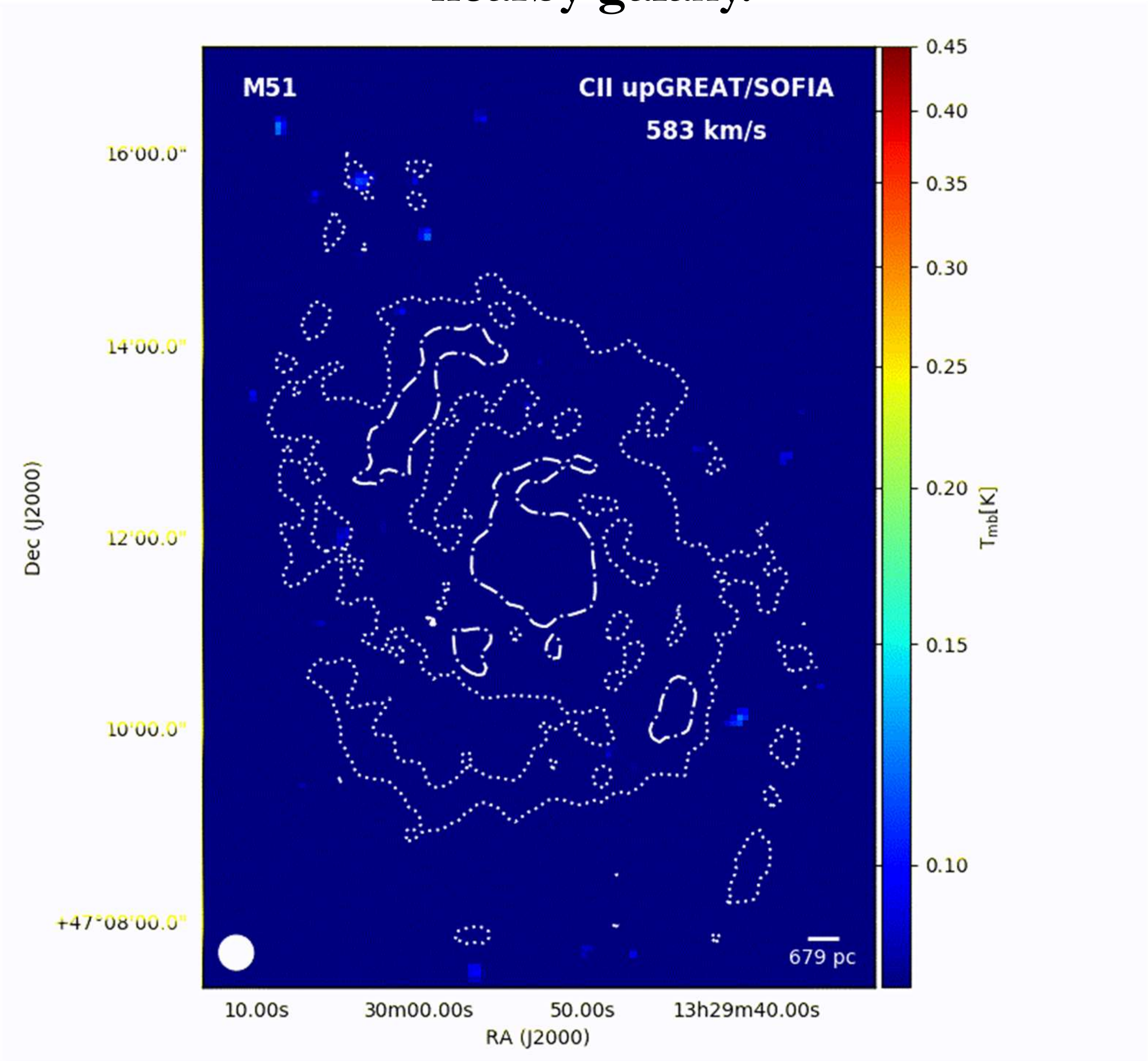
[CII], CO, FUV, etc variation across arms.

- Light-grey denotes azimuthal distribution of K-band optical observations, tracing the gravitational potential.
- A variation of the CO, [CII], and FUV peaks across spiral arms can be seen at different radii.
- If the lag increase systematically with Galactocentric radii, the lag between the tracers can be used to estimate the time scale of ISM evolution. This is expected for the density wave theory with a stationary spiral pattern (Lin & Shu 1964).
- No systematic radial trend found in the data.
- Note that a stationary spiral pattern might not be present in M51 due to its interaction with M51b.

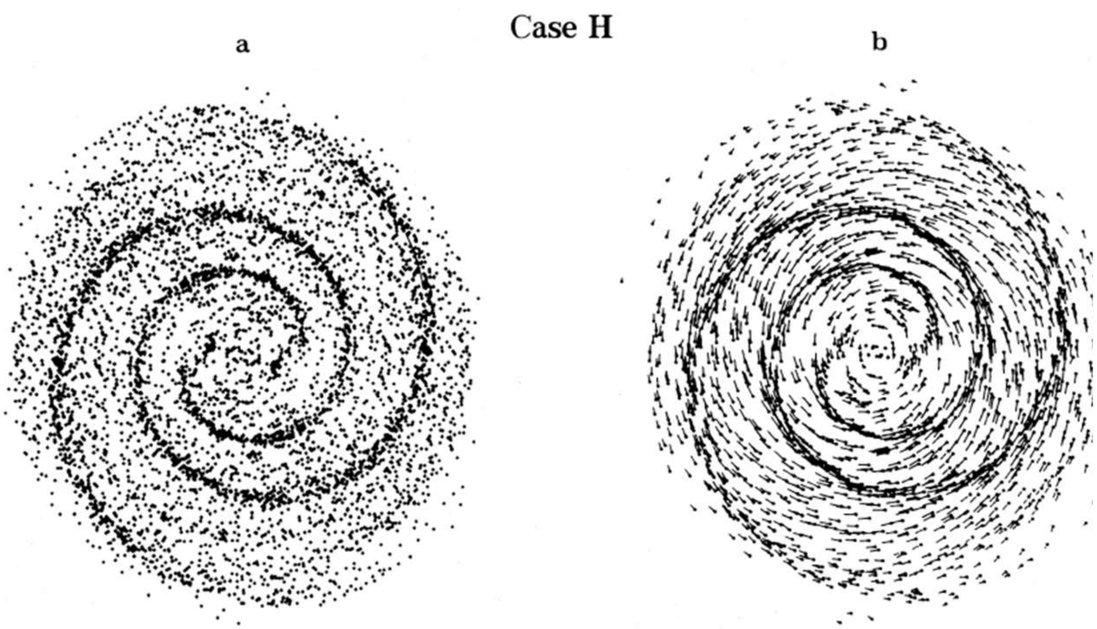
Azimuthal intensity distribution for different radii.



The M51 map is the first spectrally resolved map of a complete nearby galaxy.



Spiral Density Waves



- N-body simulations of galaxy disks suggest that spiral arms are formed by the crowding of particle orbits.
- Gas velocity discontinuities are expected in this case.

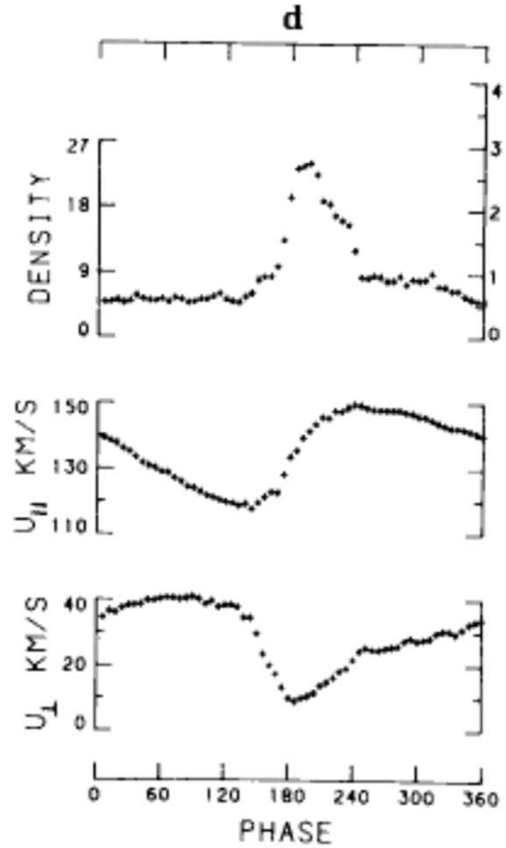
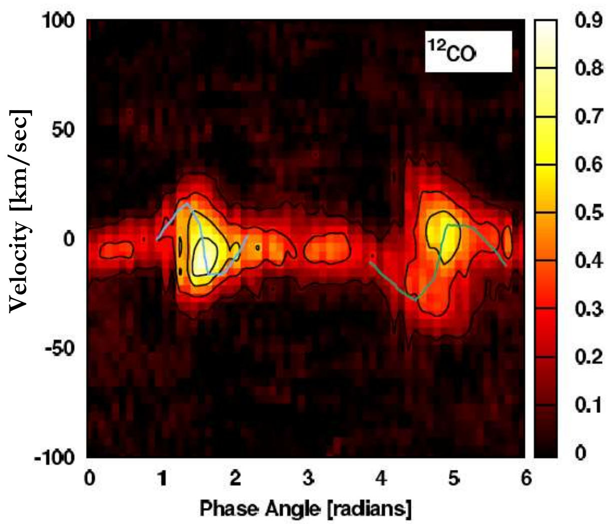
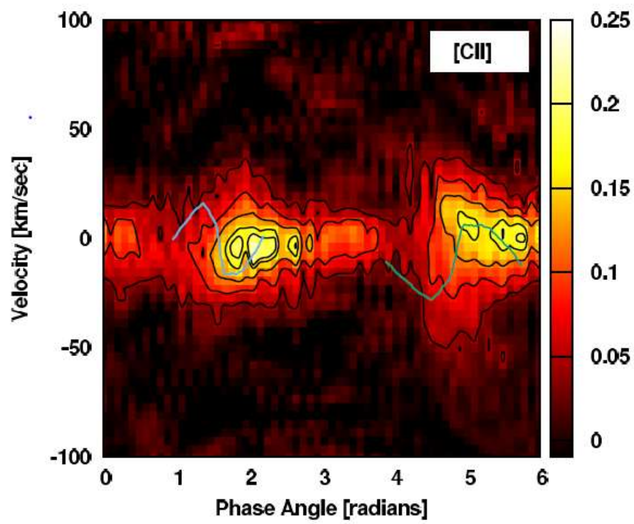


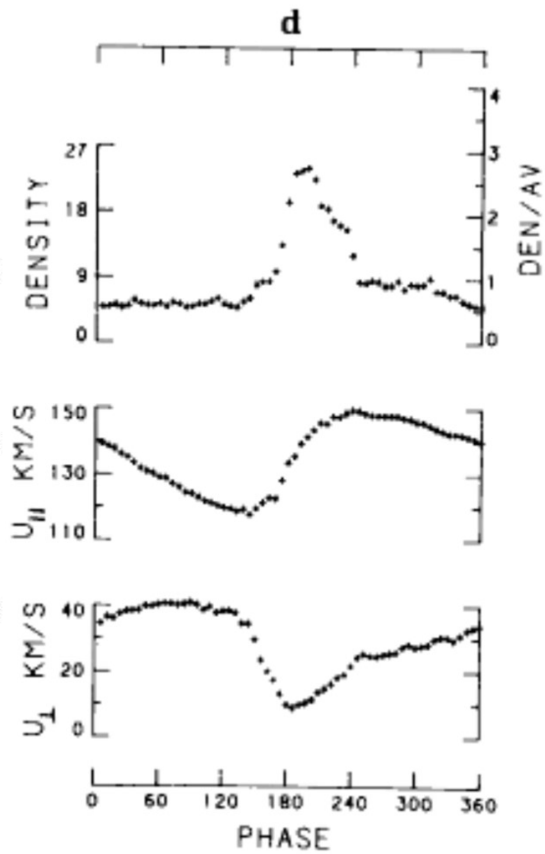
FIG. 5.—Cloud density (*top*) and velocity components (*middle*, tangential; *bottom*, radial) plotted vs. spiral phase, from RS87 dissipative simulations, case M. For a tightly wound spiral, a cut through the spiral phase is roughly equivalent to a cut in radius. This particular figure is at a time step 1170 Myr.

Roberts et al. 1987. See more modern calculations by Baba 2016

[CII] and CO velocity structure.

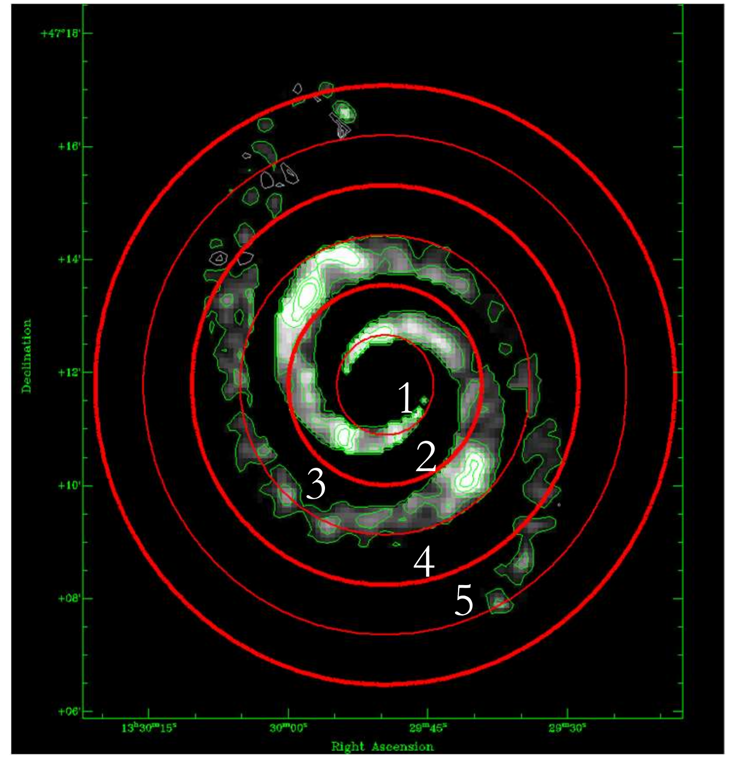






- Position Velocity Maps across spiral arms show velocity discontinuities that are possible related to spiral shocks.
- CO is being agglomerated/compressed and peak the end of the discontinuity.
- [CII] peaks right after the CO peak, suggesting that the discontinuity triggers star formation.
- Velocity distribution is in good agreement with projected theoretical predictions.
- Velocity resolved observations of [CII] and CO can be used to test theories of spiral structure.

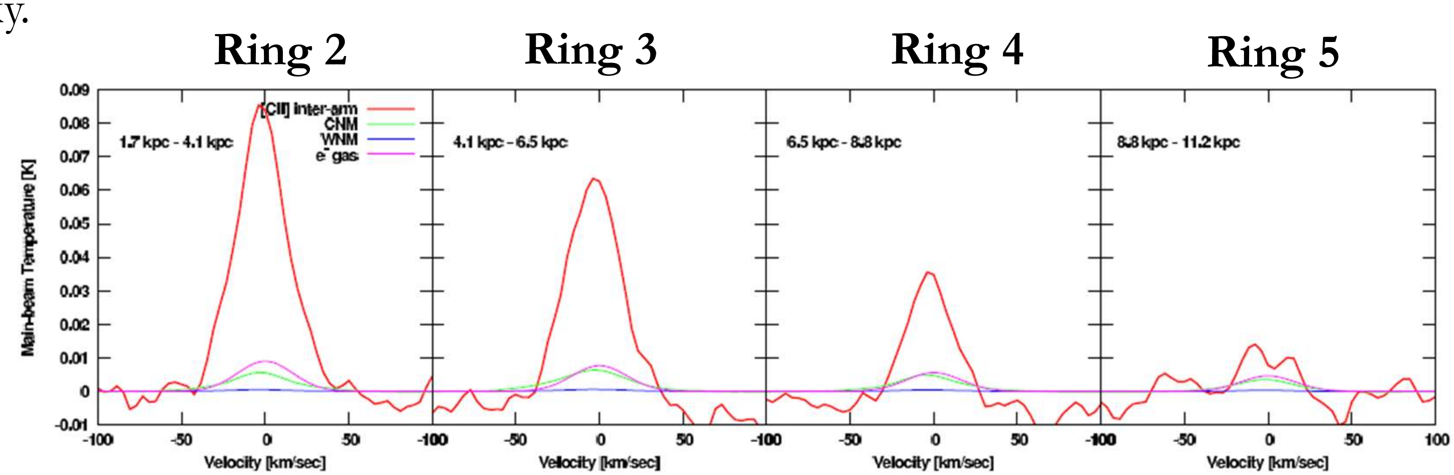
Arm vs Inter-arm regions



- Stacked spectra in radial bins show that [CII] emission in present in both arm and inter-arm regions over **all** surveyed area.

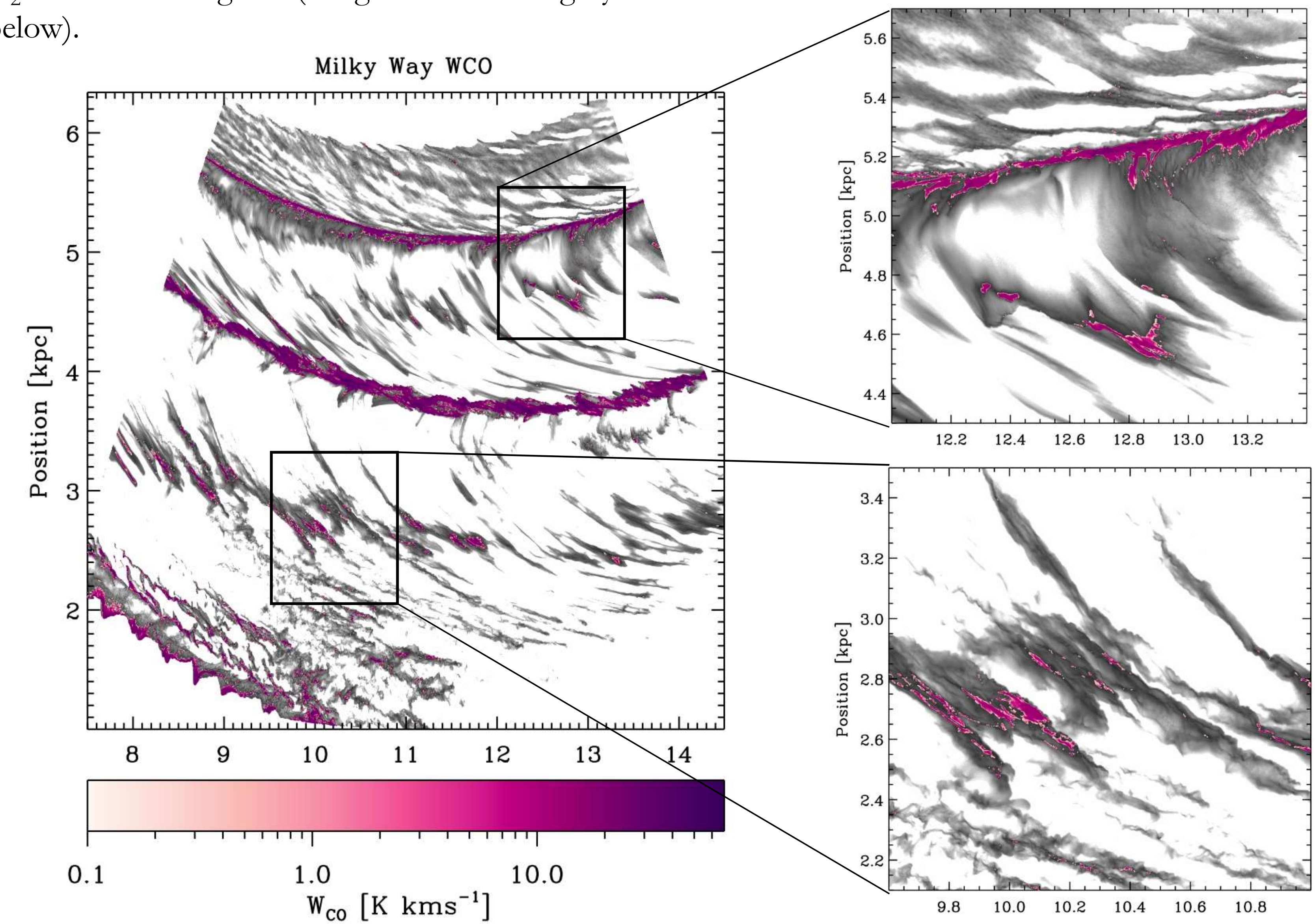
- There is a widespread diffuse [CII] component present in inter-arm regions.

- In the inner most of the [CII] comes from PDRs/CO-dark H_2. The contribution form atomic and ionized gas becomes important in the outer galaxy.



- Presence of widespread [CII] emission in spiral arms is in agreement with predictions of numerical simulations that predict large amounts of CO-dark H_2 in inter-arm regions (H2 gas is shown in grey below).

Smith et al. 2014



Summary

- The presented the first complete velocity resolved [CII] of a nearby Galaxies.
- While the [CII] and SFR are well correlated in the disk of M51, we see an example of [CII]-deficit in the companion galaxy, making this galaxy is an important laboratory in which to study the origin of this deficit seen in ULIRGS.
- We see a evolutionary sequence between CO, [CII], and FUV showing that [CII] can be used to trace the evolution of the ISM in spiral arms.
- The distribution of gas in position-velocity space shows a velocity discontinuity resulting form the presence of spiral density waves in which CO is compressed and star formation, traced by [CII], is triggered.
- When stacked together [CII] detected in the whole observed area, suggesting the presence of CO-dark H_2 gas in inter-arm and outer galaxy regions.