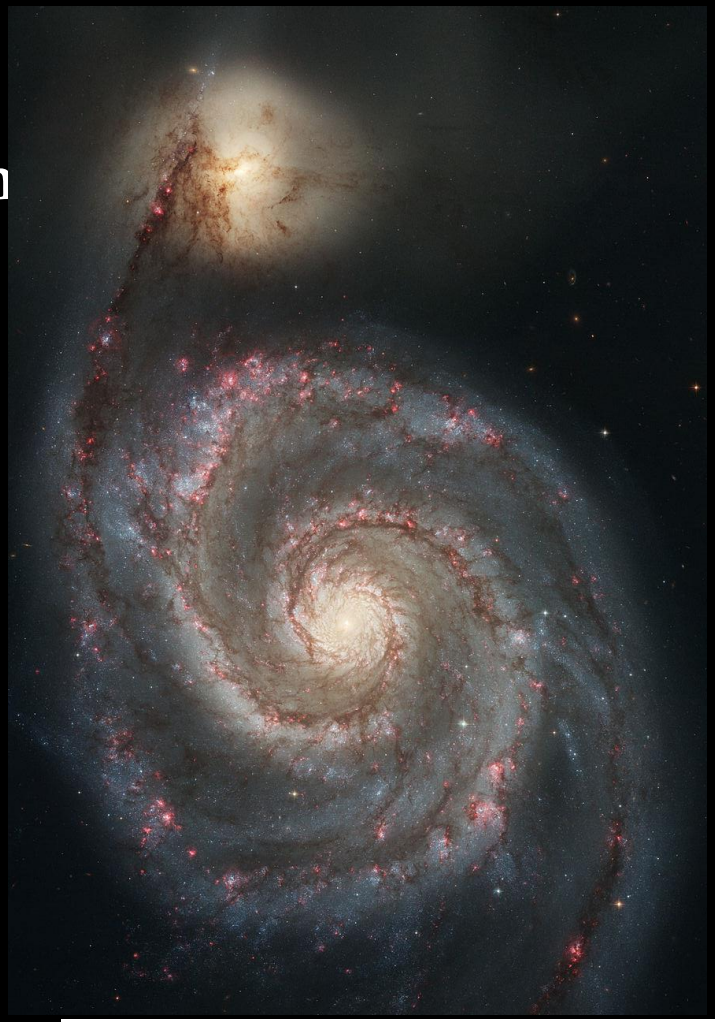
SOFIA Joint Impact Proposal:

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
Jet Propulsion Laboratory
California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Jurgen 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

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.

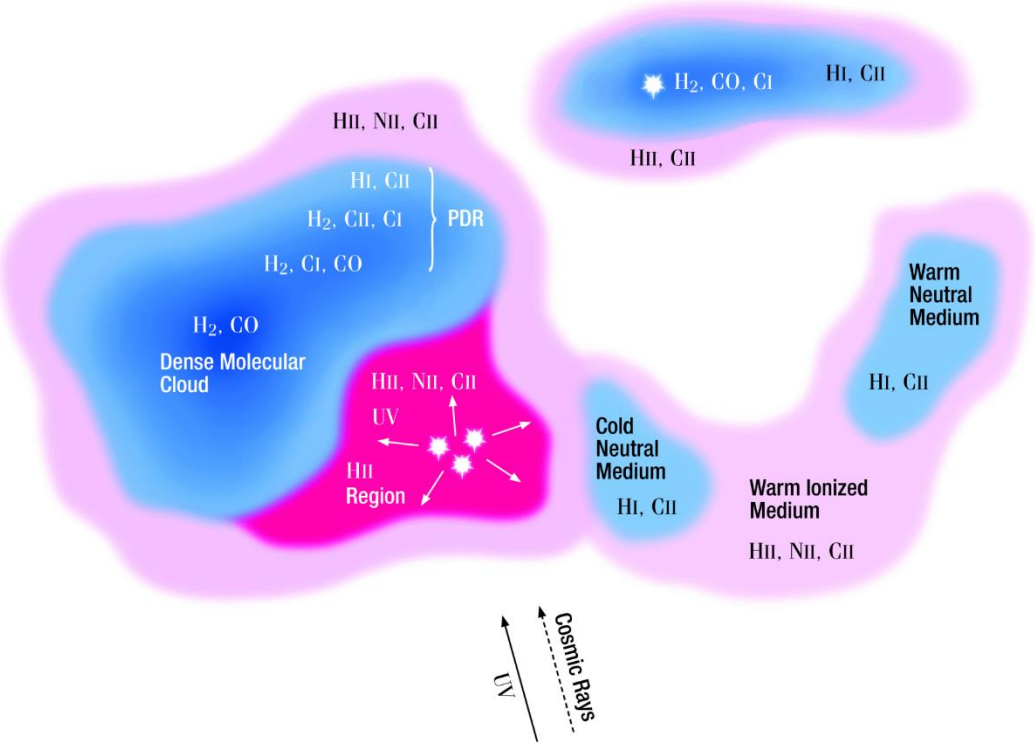
- In nearby star forming regions, small scale stellar feedback processes can be studied in detail.

- 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).

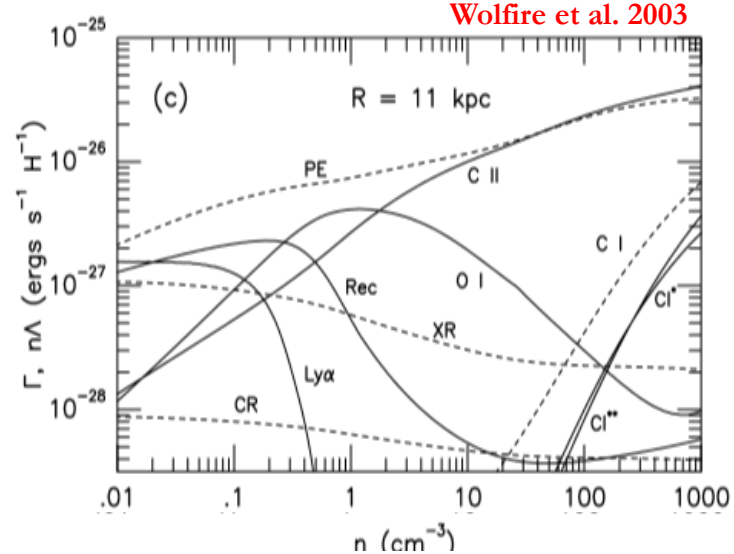


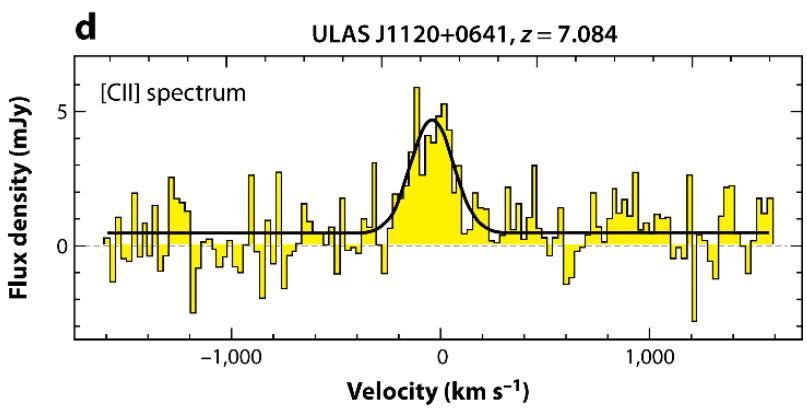
Photon-dominated region (PDR): Region where the chemistry and thermal balance is dominated by the far-ultraviolet radiation field from massive stars.

The [CII] 158um Line

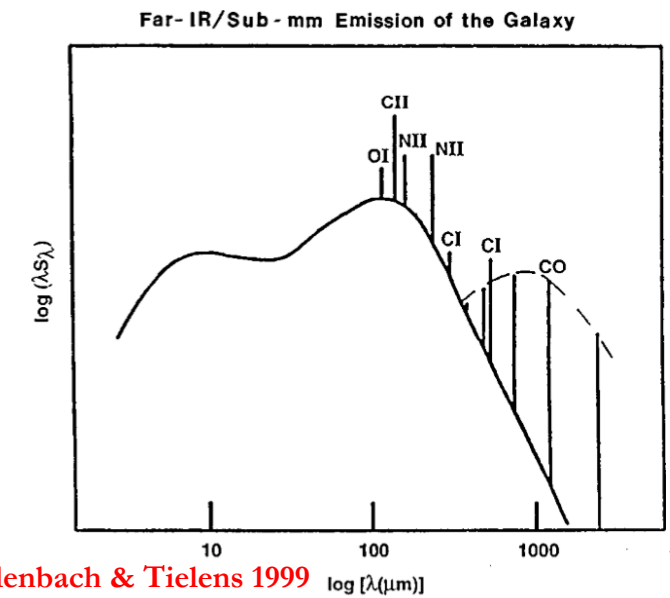
- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM.
- It represents 0.1 to 1% of the total far-infrared continuum, and it is the brightest FIR line.
- Thus, the CII line is a tracer of star formation in galaxies.

Wolfire et al. 2003





Wang et al. 2013 ApJ 773, 44

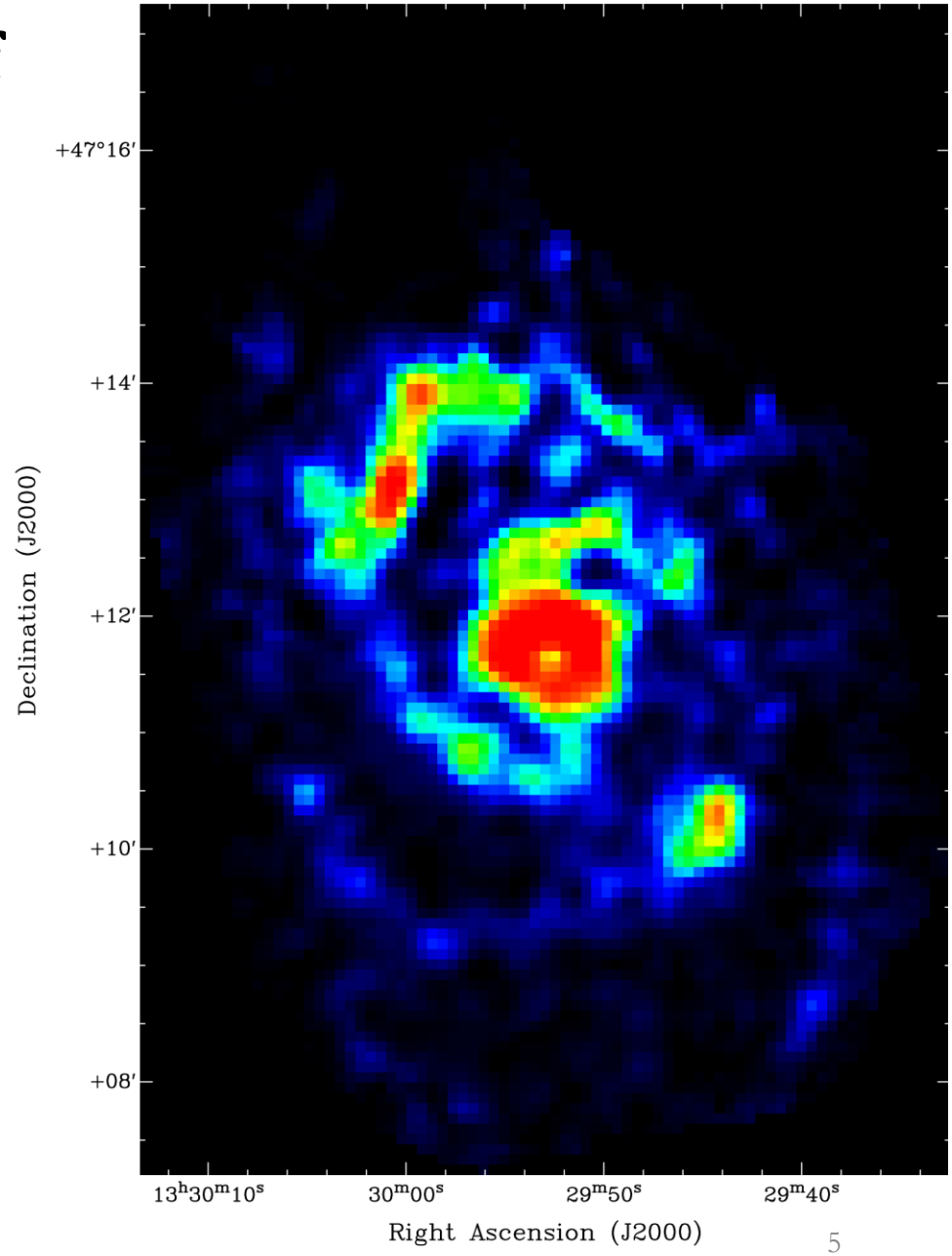


Hollenbach & Tielens 1999

The SOFIA [CII] Map of M51

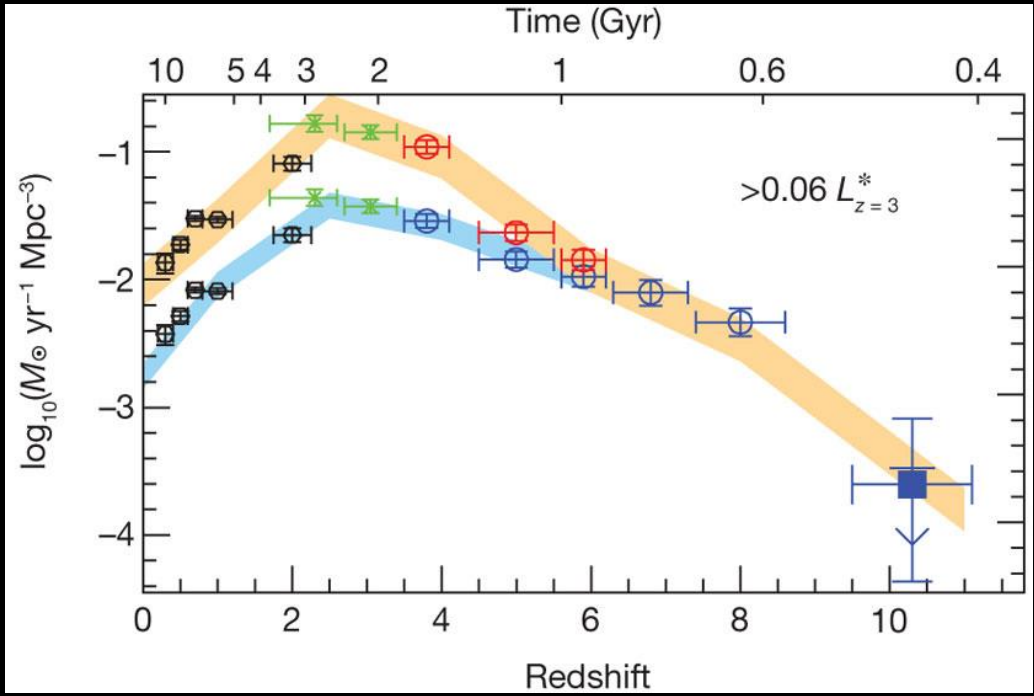
- Joint impact project between US and German institutions.
- 75h of observing time over several SOFIA Cycles.
- 80% US time and 20% German time.
- **upGREAT** observations for resolving the spiral arms in velocity space.
- **FIFI-LS** observations for sensitive observations of [CII] in the inter-arm regions.

upGREAT Map of M51



The star formation rate

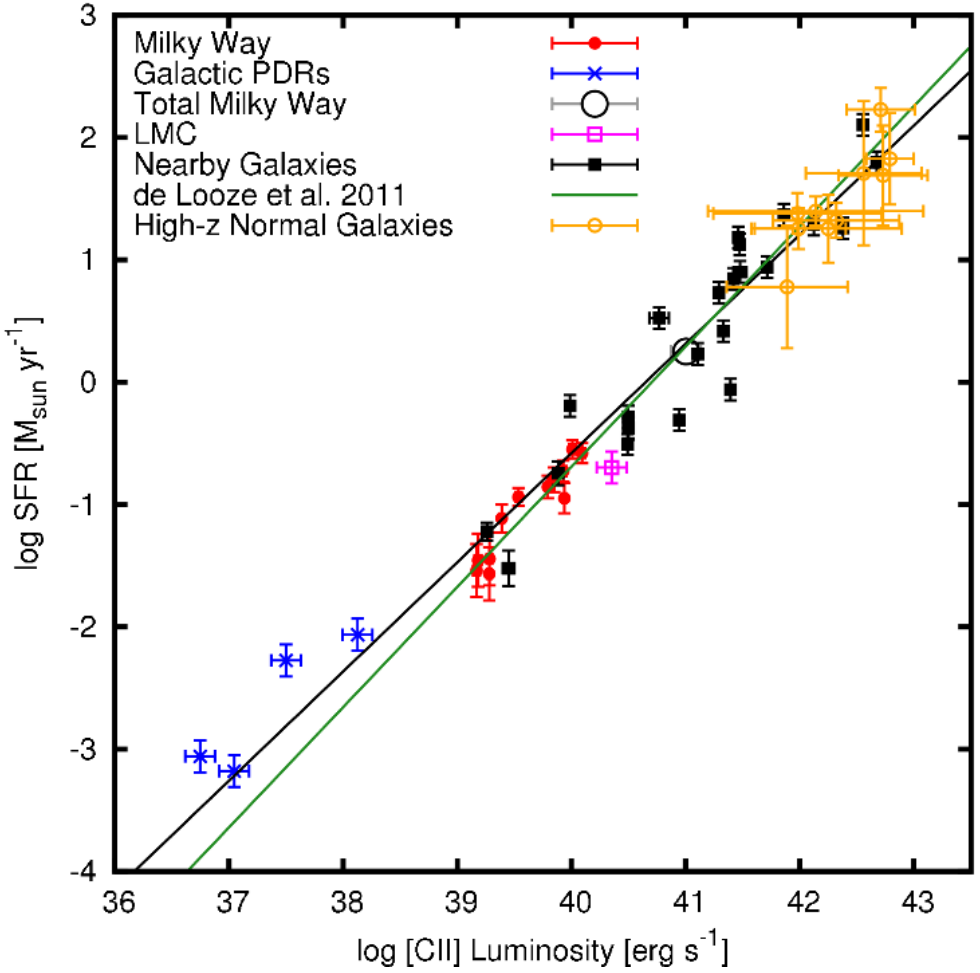
- An important parameter used to characterize star formation in galaxies over cosmic time.
- The peak of star formation in the Universe occurred at redshift Z=2.
- It is important to find tracers of star formation that can be observed in galaxies over a wide range of redshifts.



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.

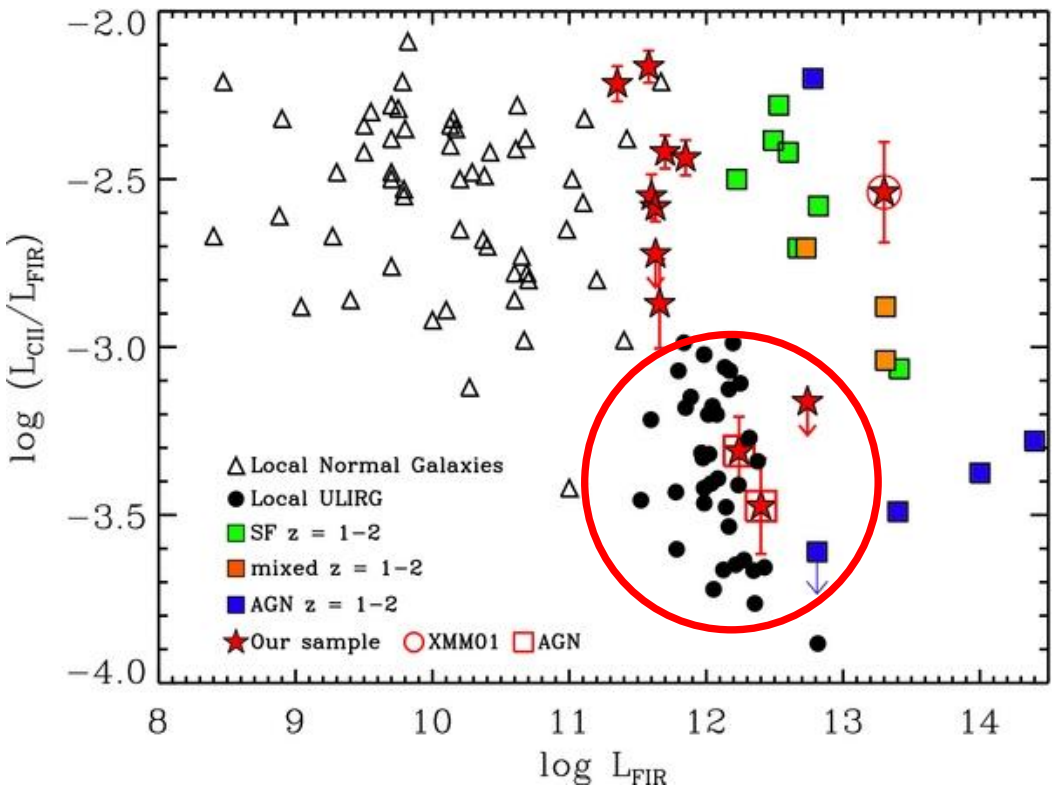
- The [CII]-SFR correlation extended over several orders of magnitudes in these quantities.



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]

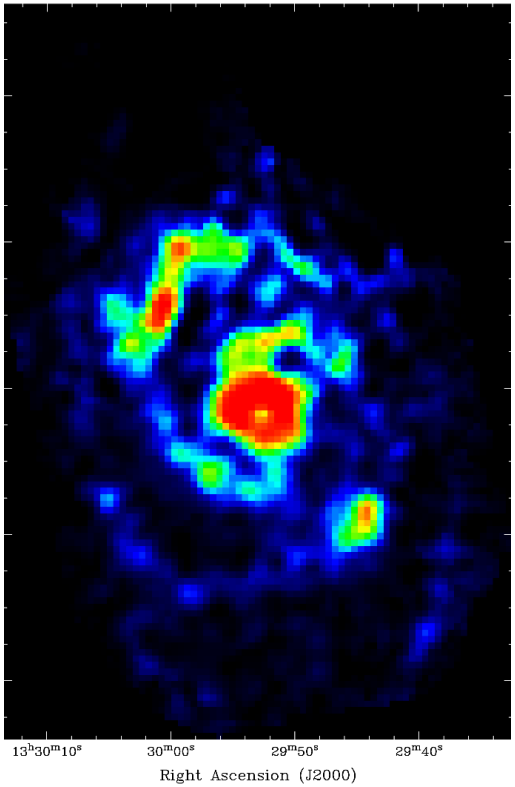
- A complete [CII] map in M51 allow us to study its relationship with star formation over a wide range of environments.

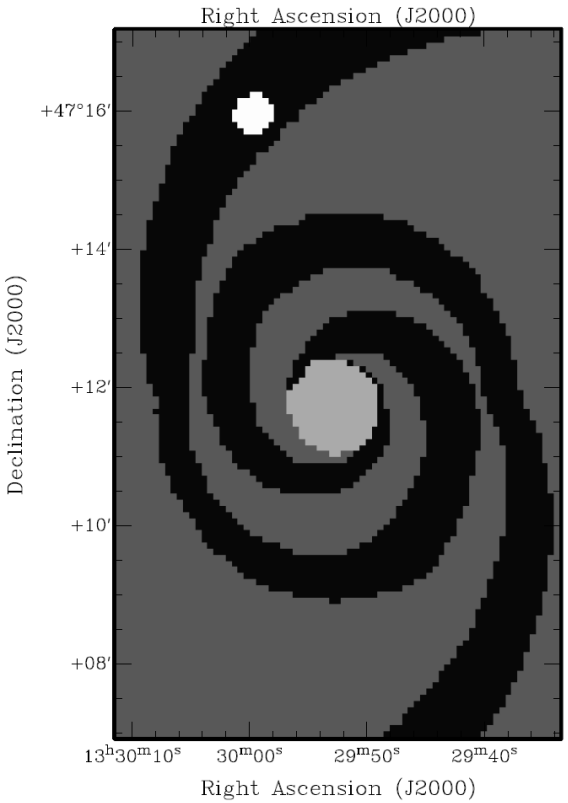
- We defined four environments: M51's center, Spiral arms, inter-arm regions, and M51b.

- 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)





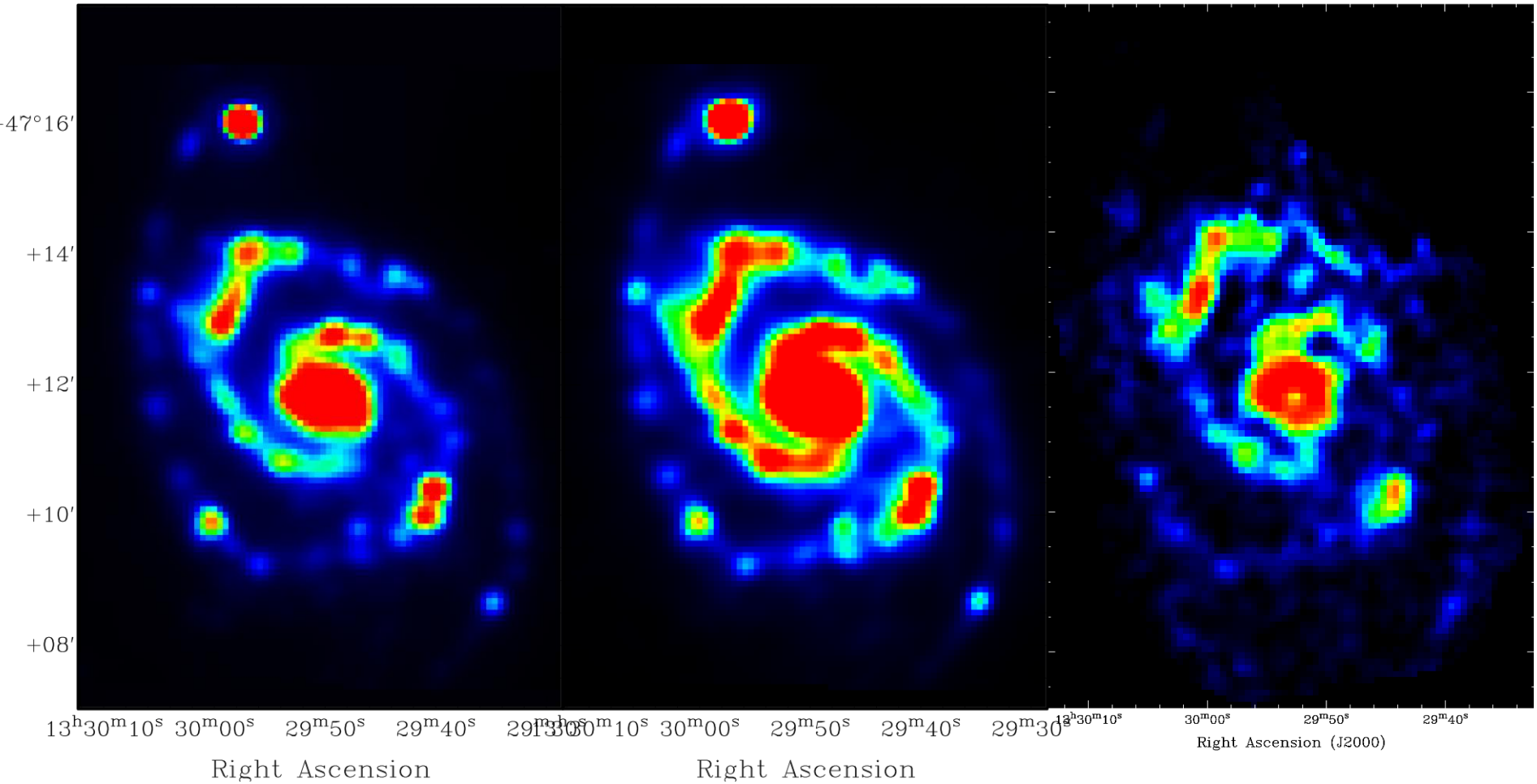
Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

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

M51 Star formation rate

M51 in Total IR

M51 in [CII]

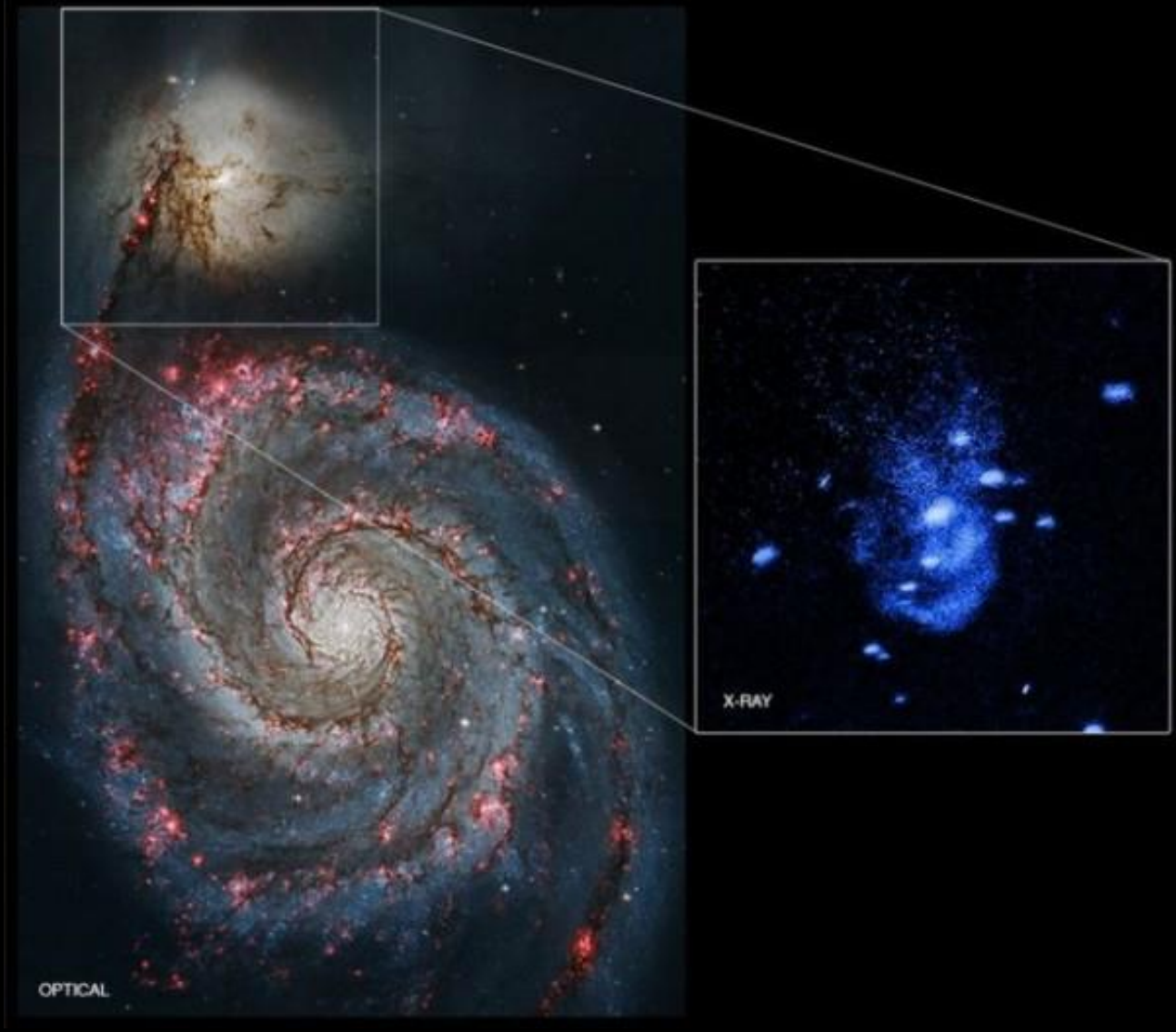


SFR=Ha+24um

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

M51b

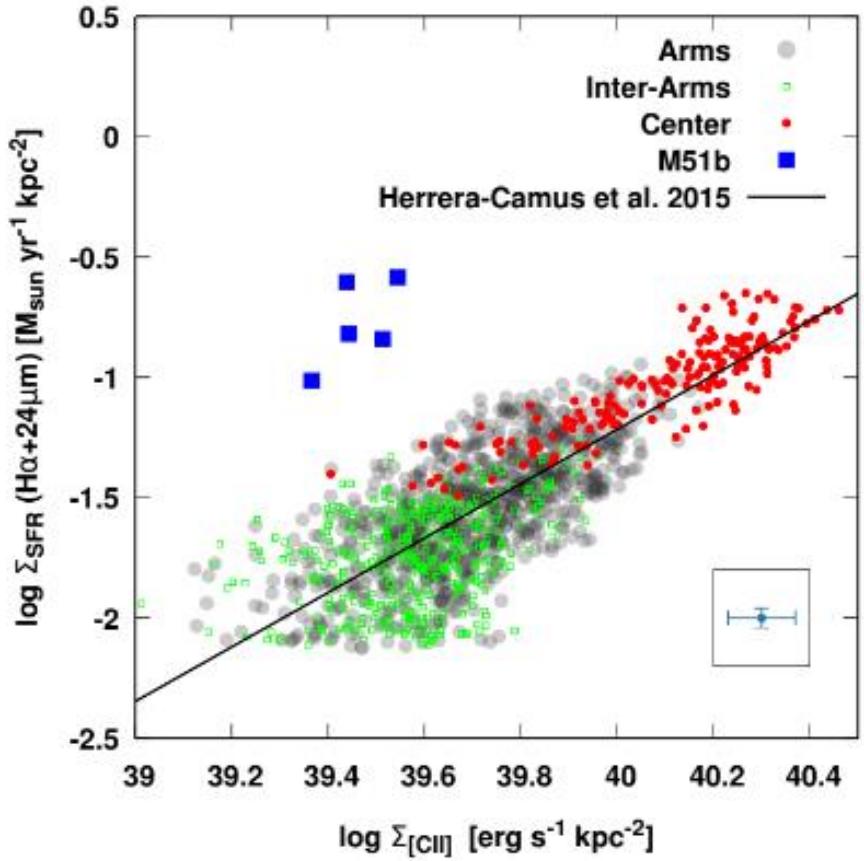
- The closest super massive black hole is in NGC 5195.
- X-ray emission shock arcs shows that gas is being pushed away.
- Closest example of AGN feedback.



Schlegel et al. 2016

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

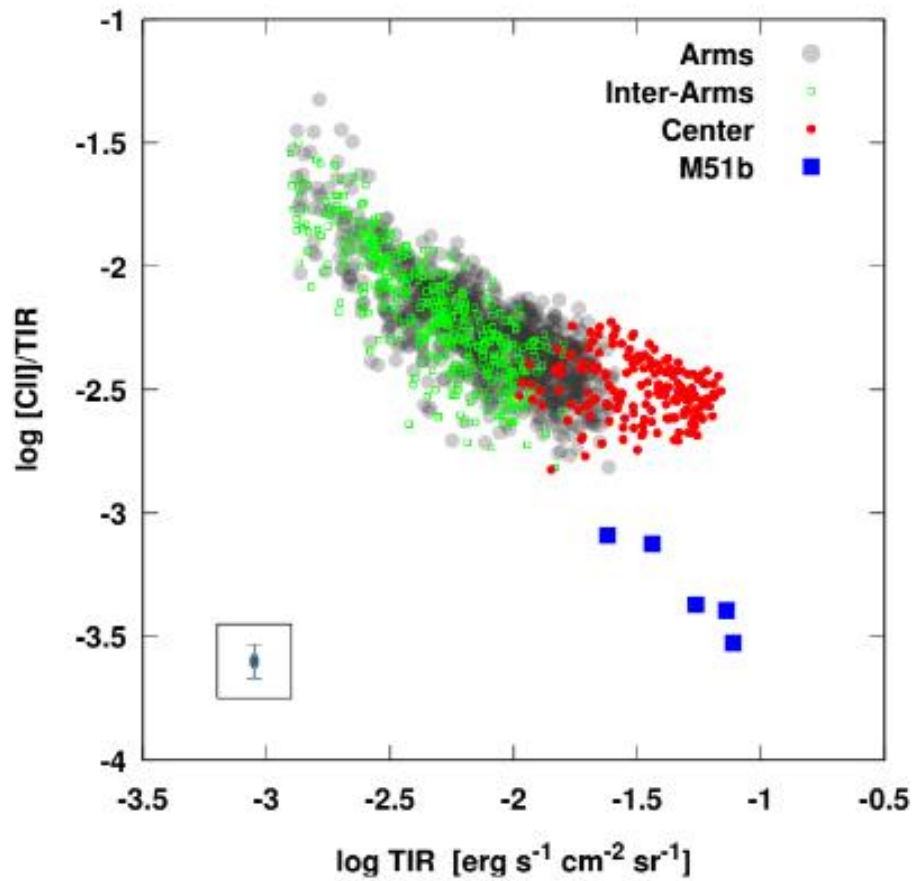
- [CII] and the SFR are well correlated in the disk of M51 (arms, inter-arms, and galactic center).
- The [CII]-SFR relationship is similar to that in the Milky Way and other nearby galaxies (black straight line is fit to *Herschel*/KINGFISH galaxies).
- But the companion galaxy, NGC5195 shows a deficit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

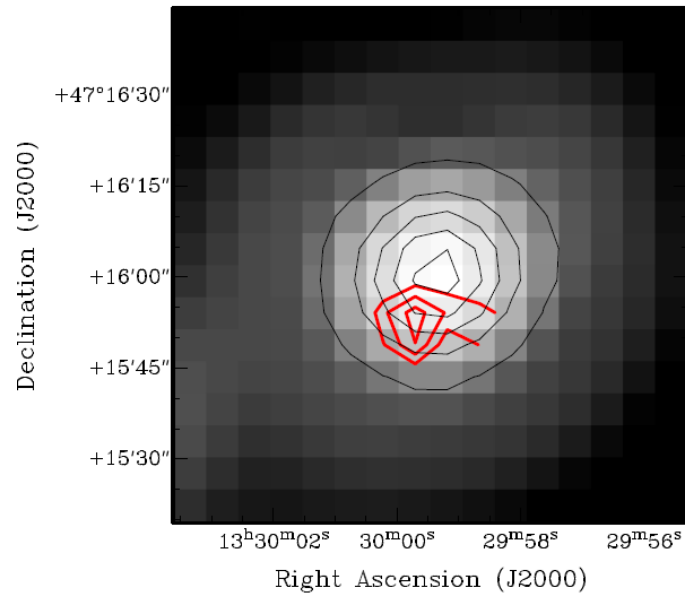
- The disk of M51 has a [CII]/TIR ratio that is typical of normal galaxies (10^{-3}-10^{-2}).
- But companion galaxy shows much lower [CII]/TIR ratios.
- Such low values are typical of ULIRGs (Diaz-Santos 2014).
- But note that the TIR luminosity is at least two orders of magnitude lower than those in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

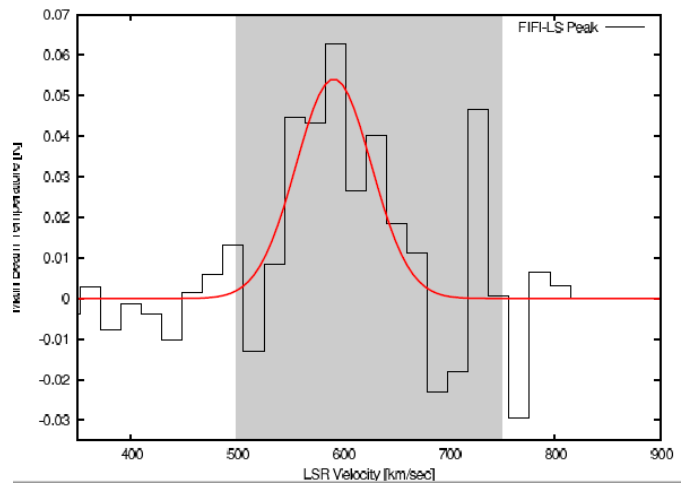


Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

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 (JWST).
- Herschel/PACS [OI] 63um and [OI] 146um reduce deficit by 50%.
- ***M51b is an important nearby laboratory to study the deficit of [CII] emission in galactic nuclei.***

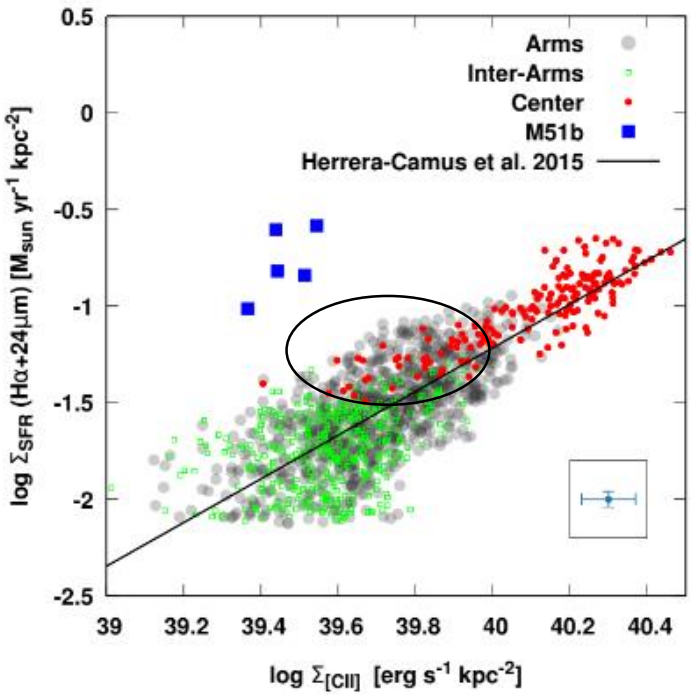


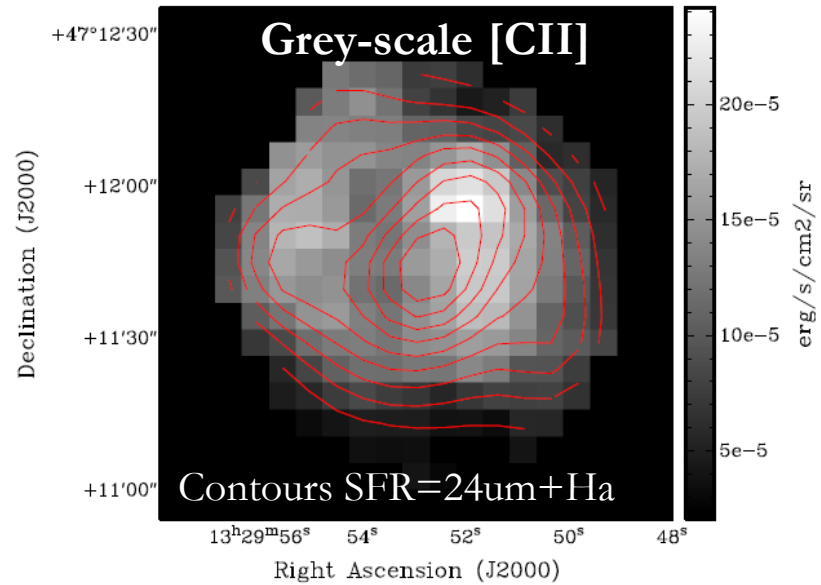


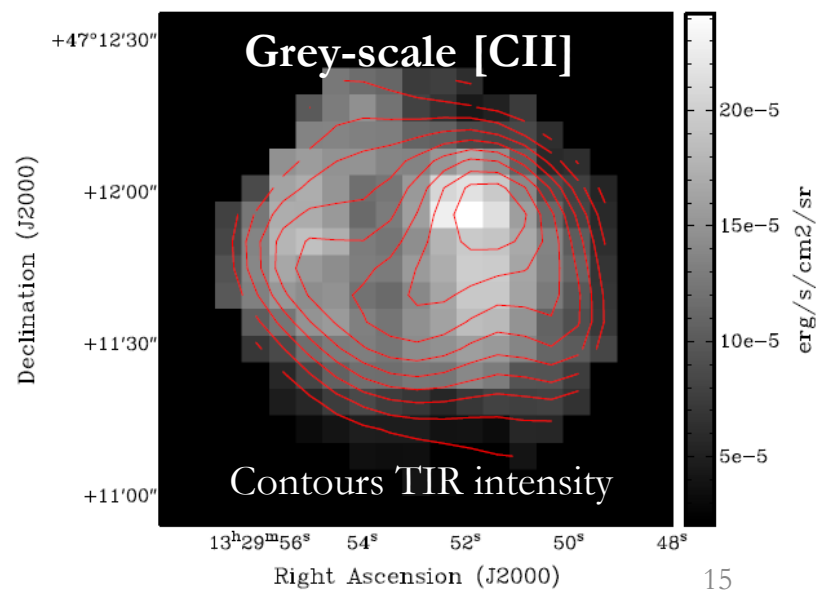
Pineda, Fischer, Kapala, Stutzki, et al. 2018, 869, L30

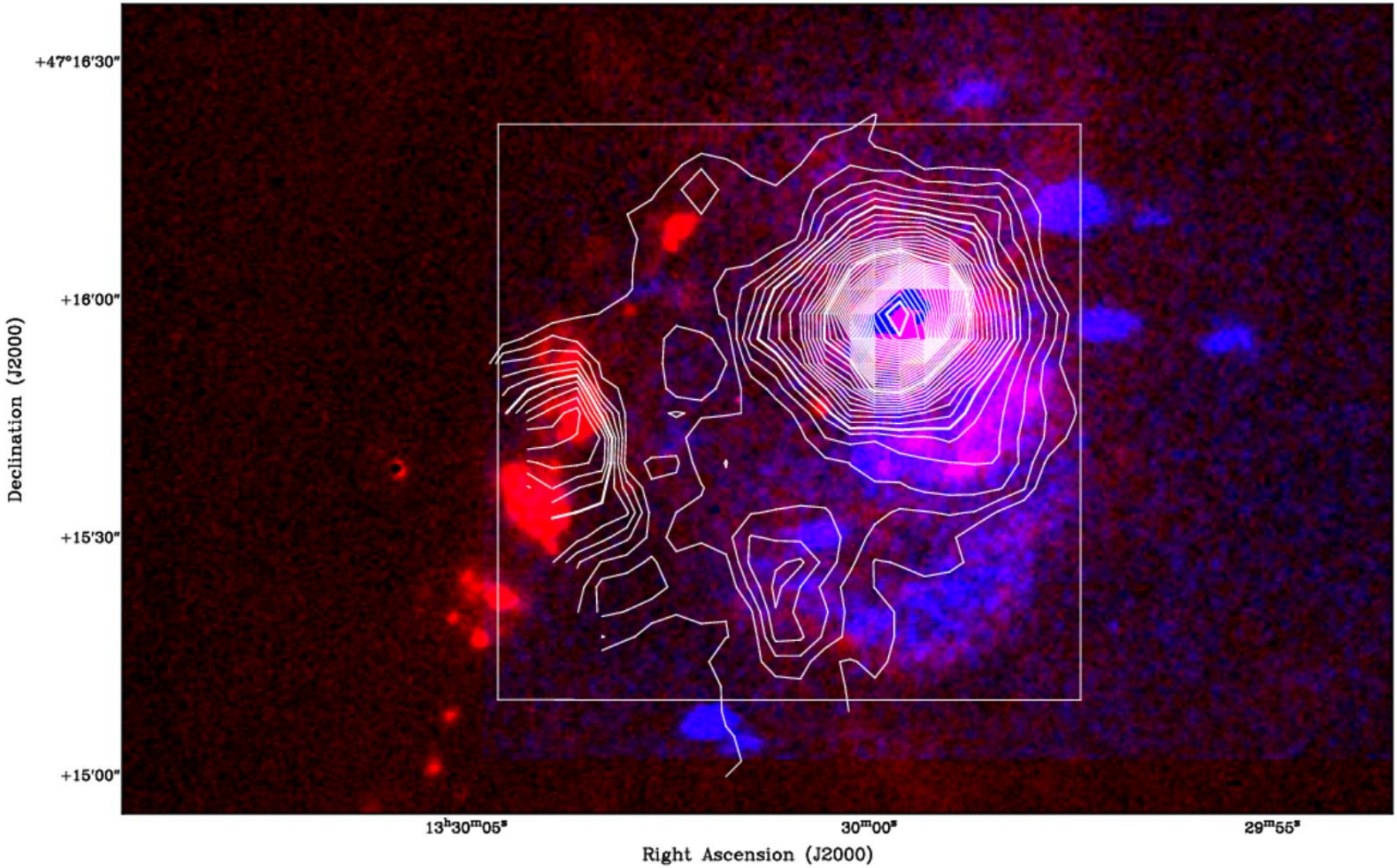
Some deficit is seen in M51's center.

- 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.









- There is [CII] gas connecting the M51b and M51.

- Velocity resolved observation can be used to determine the gas transport between M51 and M51b.

Summary

- The presented the first complete velocity resolved [CII] of a nearby Galaxy.
- 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.
- [OI] cooling can account for 50% of the deficit.
- M51b is a important neaby laboratory to study AGN feedback and the mass transport between galaxies as a result of tidal interaction.