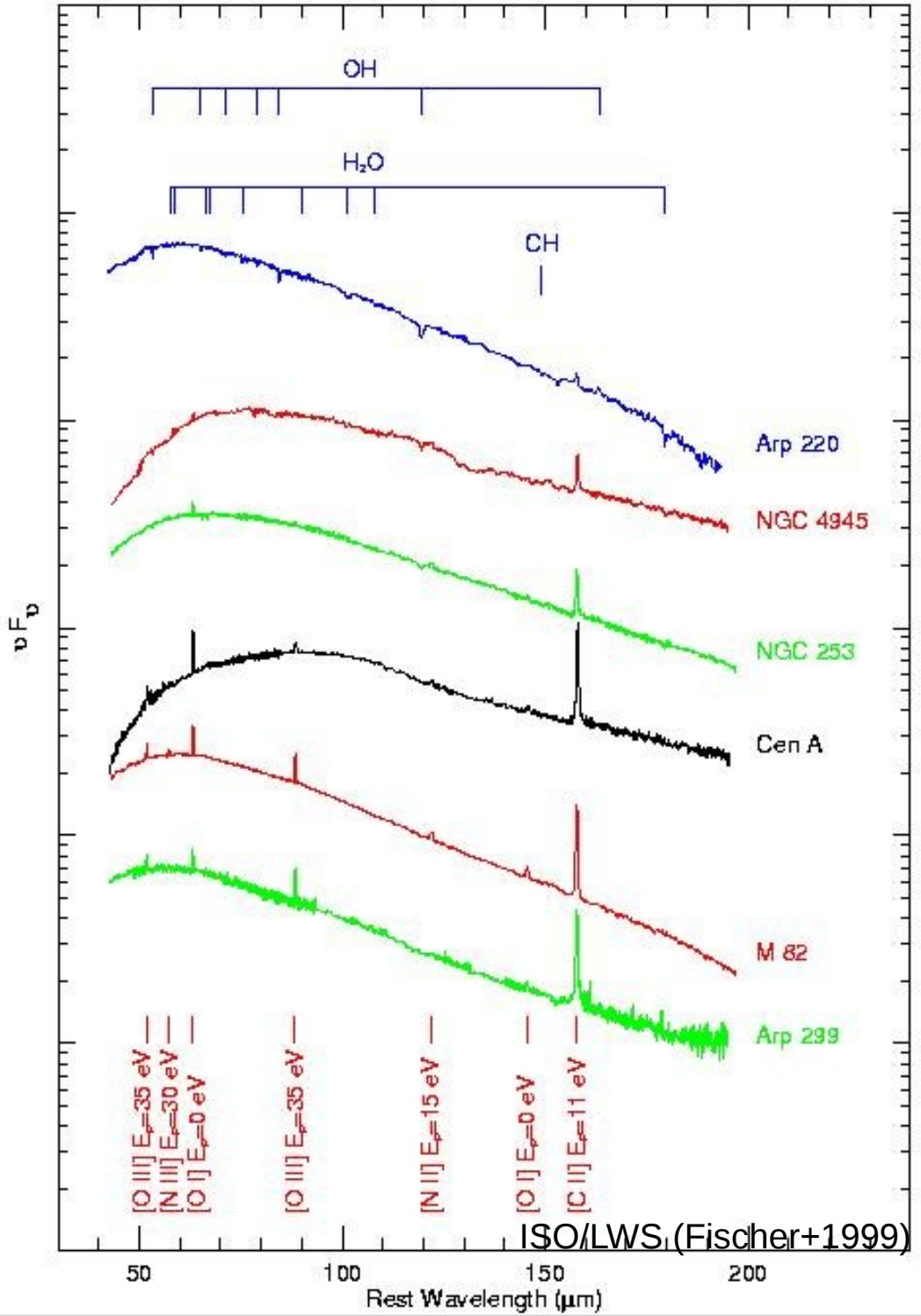
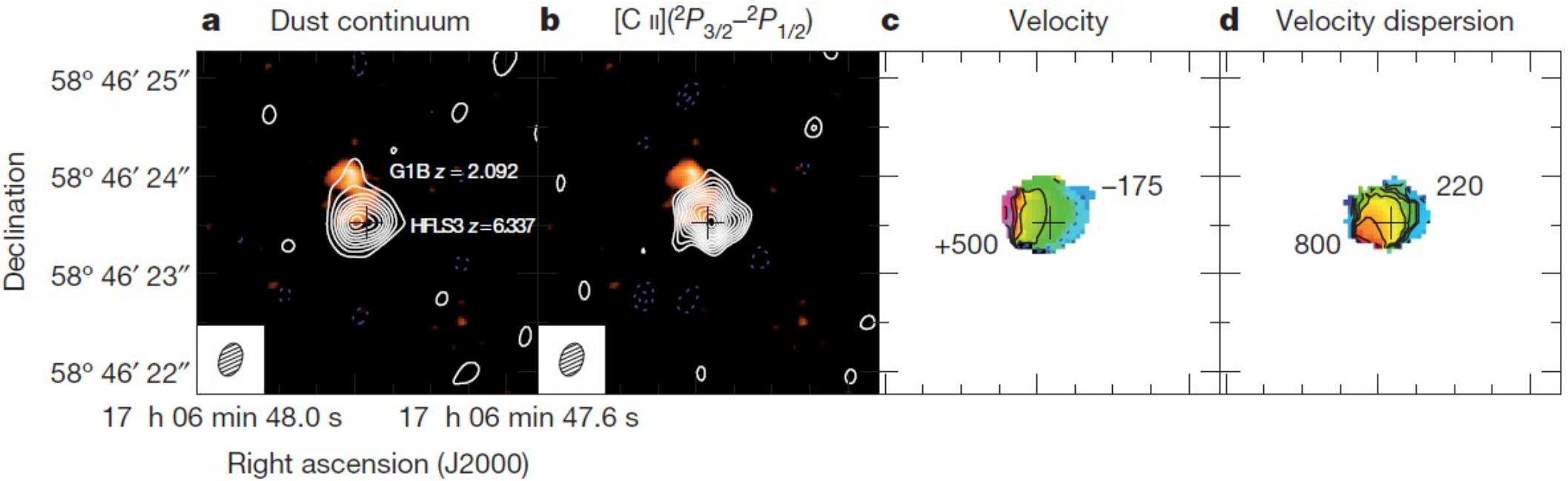
Nearby Galaxies: FIR Cooling Lines

Carsten Kramer (IRAM)



ISO/LWS (Fischer+1999)

[CII] line emission at z=6.34 : velocity information



PdBI/NOEMA observations of the [CII] line 1.1mm and at 0.3" resolution by Riechers+2013 in the massive starburst galaxy HFLS3: emission covers a region of 1.7kpc radius (=resolution), star formation rate ~ 2900 M_{sun}/yr, velocity contours in steps of 100 kms^{-1}, large velocity dispersion of up to 800 kms^{-1} (strong winds ?).

+ [CII]/FIR ~ $5x10^{-4}$ low but typical.
+ [CII] by far the strongest line, [CII]/CO 1-0 = 3100
+ [CII] used to estimate HI mass

Where does the [CII] stem from ?

Nearby Galaxies – FIR lines: Overview and Scope

The origin of [CII]

+ Going from scales of kpc to 50pc: integrated intensities

    + Dense ionized gas and small grains: Star formation rate

    + Dense gas

    + Diffuse ionized and neutral gas

    + Dust: Total infrared continuum (TIR)

+ Velocity information at 50pc

Star Formation

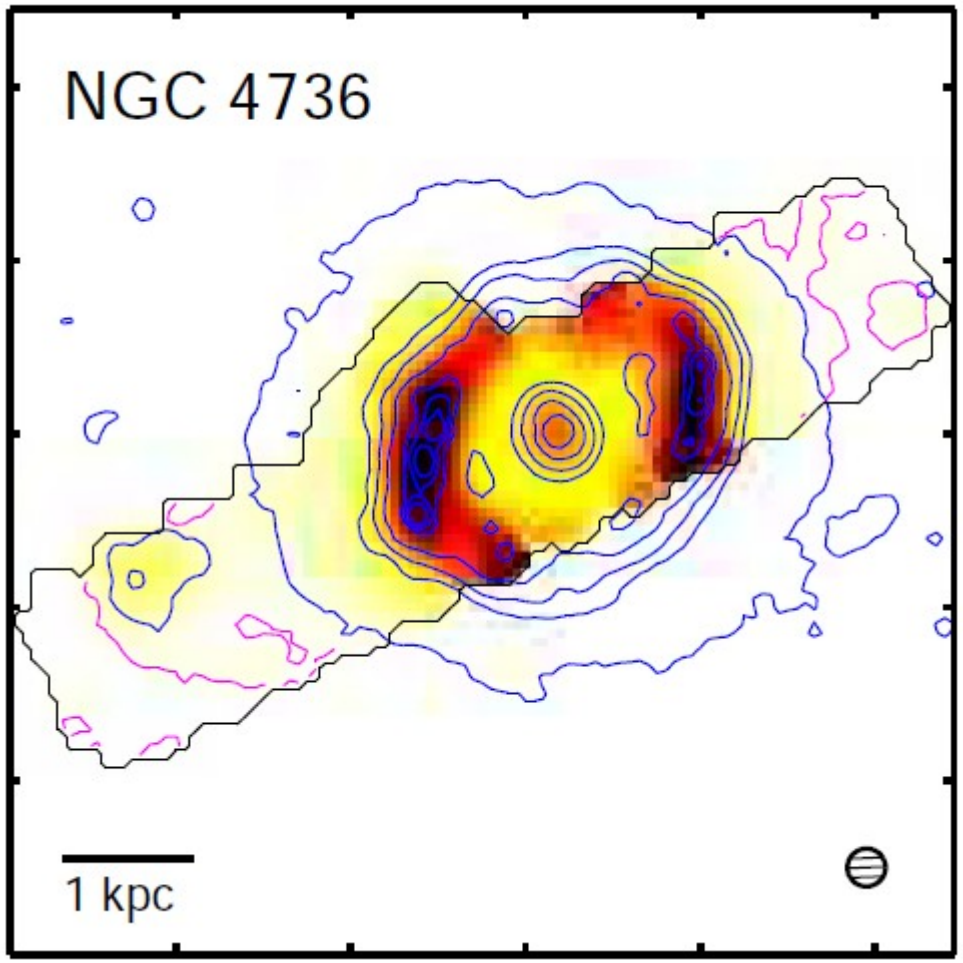
[CII] tracing the Star Formation Rate: A simple picture

Star forming regions with their OB stars produce UV photons which heat the dust. Photoelectrons are thermalized heating the gas. And collisions with H_2, H, e^- excite C^+ which cools the gas by emitting the 158μm line.

The [CII] line measures the total energy that is put into the gas by the star formation activity.

It is useful to calibrate this relation as this line is very bright, and unaffected by extinction. Useful for high-z studies.

Herrera-Camus+2015

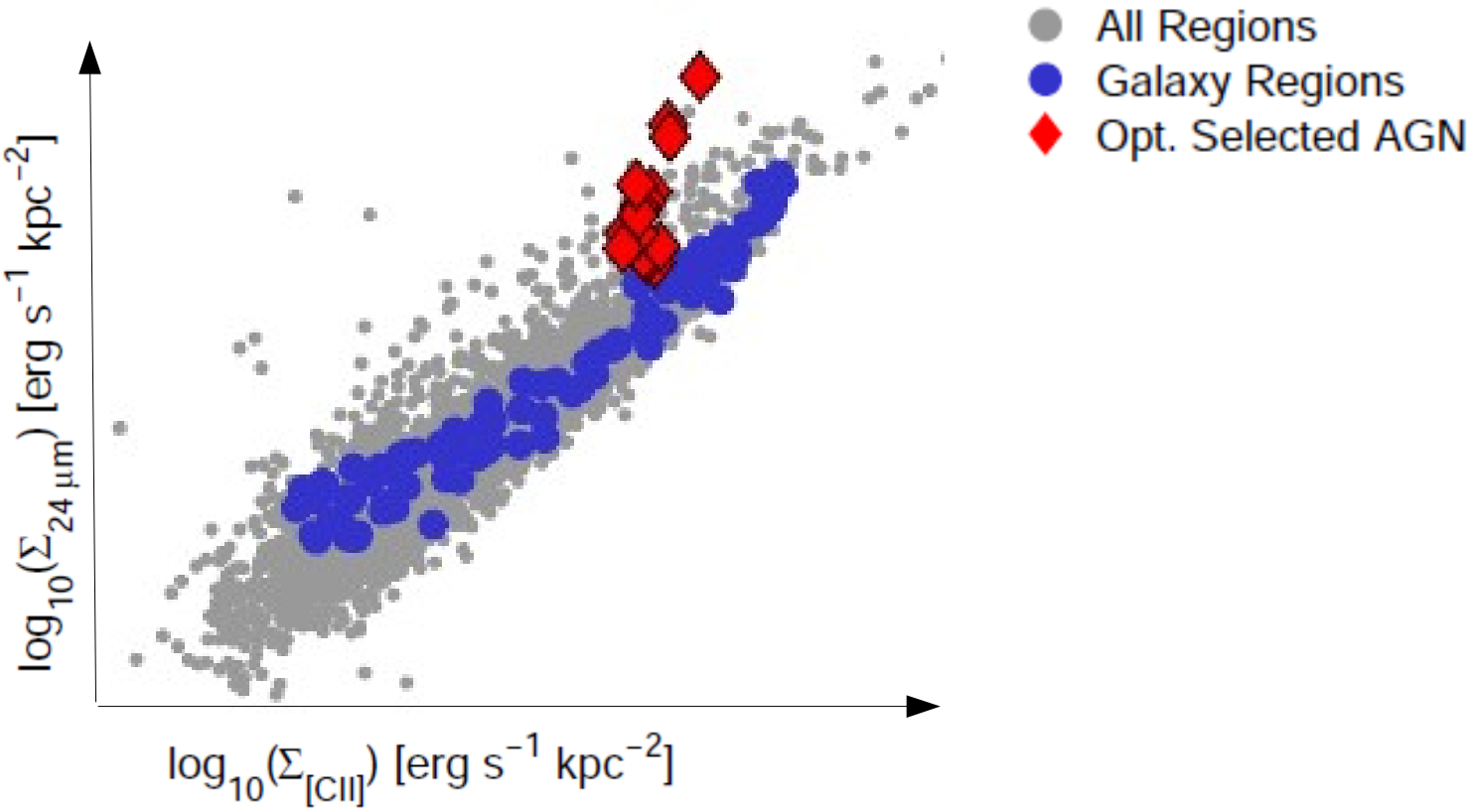


[CII] image and 24μm emission (blue contours).

Herrera-Camus+2015 use PACS to map [CII] in 46 nearby galaxies with 12” resolution – KINGFISH key project. One example is NGC4736. At this scale, the correlation with 24μm is very good.

[CII] tracing the Star Formation Rate... or not

24μm vs. [CII] in NGC4736



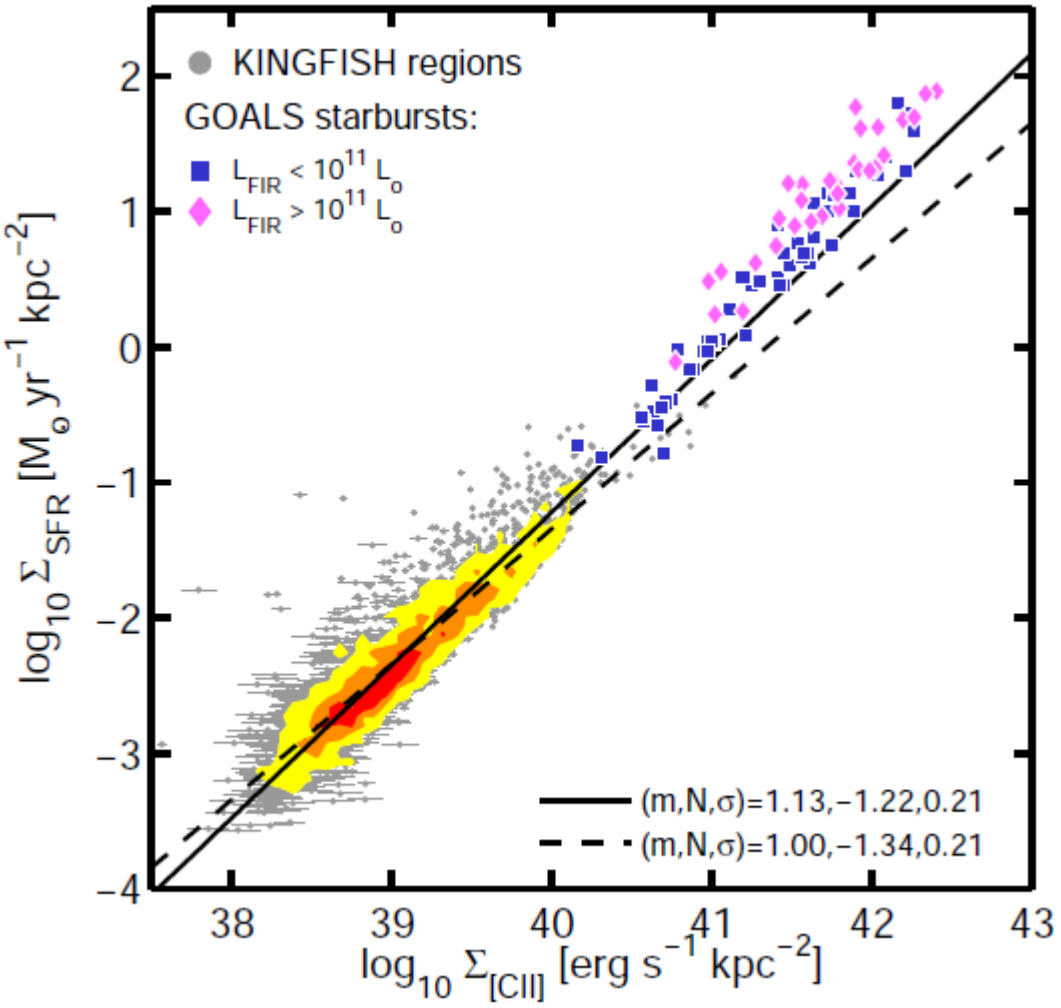
Outside of the nucleus, the correlation between 24μm and [CII] is very tight.

For the inner optical AGN, a [CII] deficit or 24μm excess shows up by a factor of 6.

X-rays may destruct PAHs and small grains, leading to a reduction of the photo-electric heating efficiency.

[CII] tracing the Star Formation Rate outside AGNs

Herrera-Camus+2015



$$\Sigma_{\rm SFR}\ ({\rm M}_\odot\ {\rm yr}^{-1}\ {\rm kpc}^{-2}) = 3.79 \times 10^{-47} \times (\Sigma_{\rm [CII]}\ [{\rm erg\ s}^{-1}\ {\rm kpc}^{-2}])^{1.13}.$$

Tight, about linear correlation between the SFR (from Hα and 24μm emission) and [CII] at scales of **~0.6 kpc**, in the absence of strong AGNs, over almost **5 orders of magnitude**.

However, there is a **[CII] deficit** at high SFR ($L > 10^{11}$ L_{sun}) even after removing AGNs ! And there is scatter.

+ **[CII] self-absorption** (cf. Gerin+2014)

+ **charging of grains** leading to reduction of photo-electric gas heating efficiency

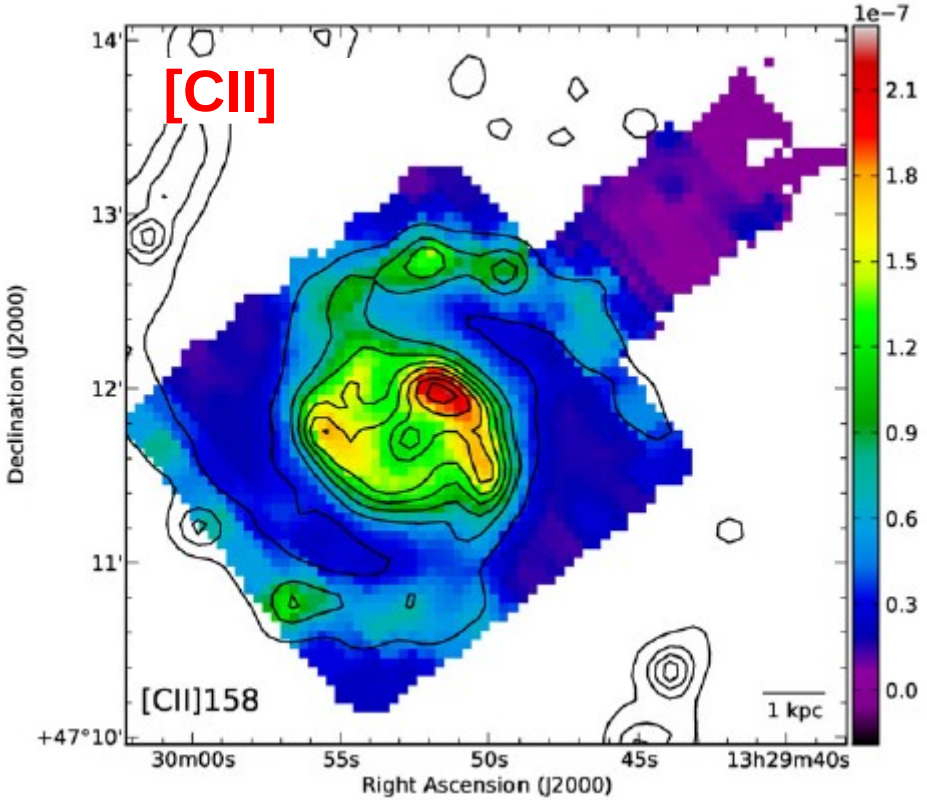
+ **[OI]** as additional cooling channel...

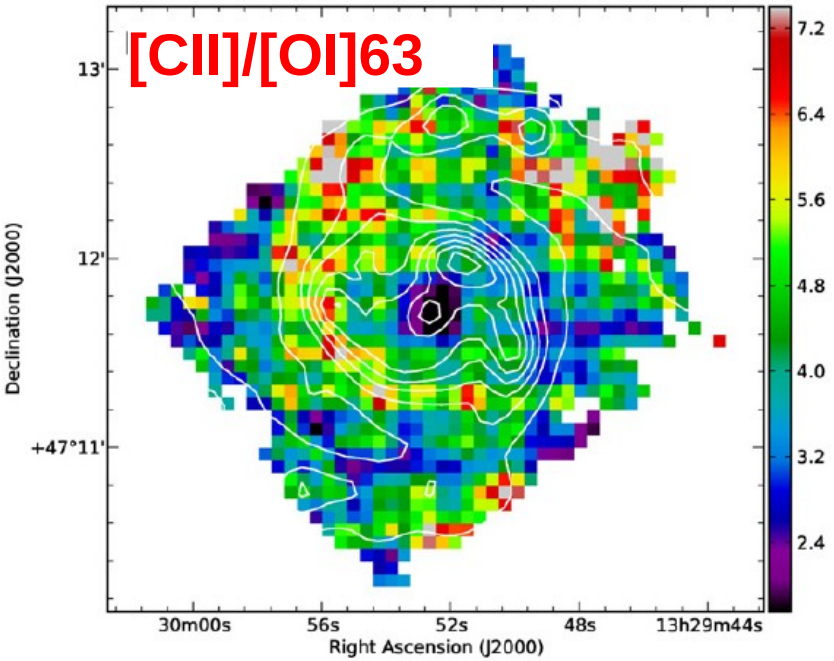
+ [CII] gas emission may be **polluted by non-SF contributions**: Diffuse atomic and ionized gas

+ Dense gas
+ Diffuse ionized gas
+ Diffuse neutral gas

Different regions of a galaxy: Dense gas

M51 at 9.9 Mpc by Parkin+2013: PACS and SPIRE observations

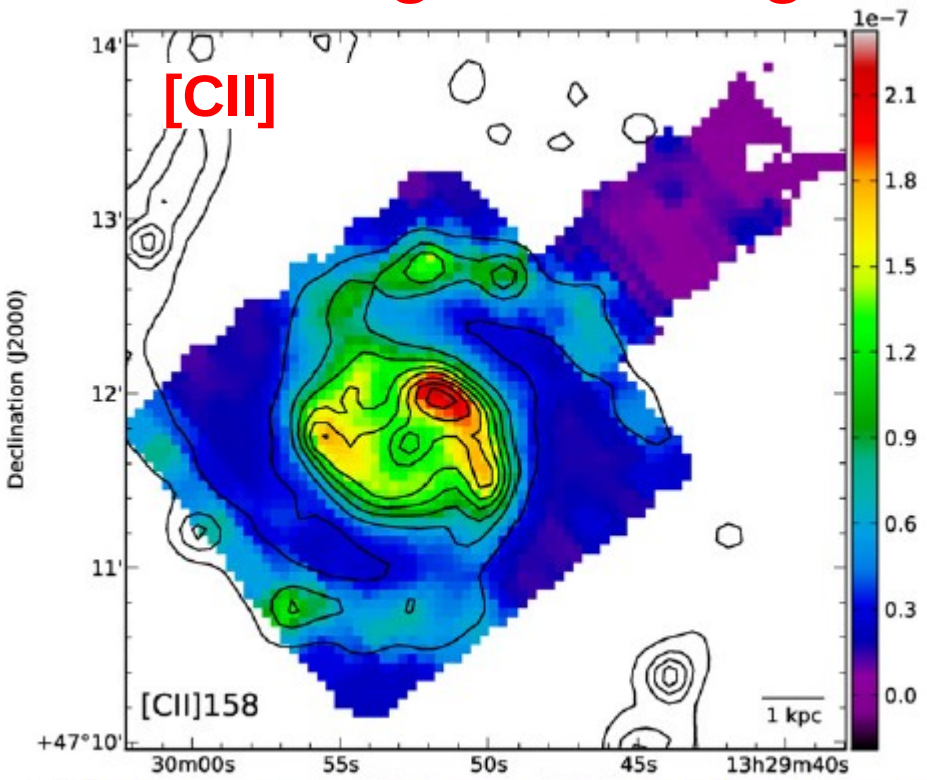


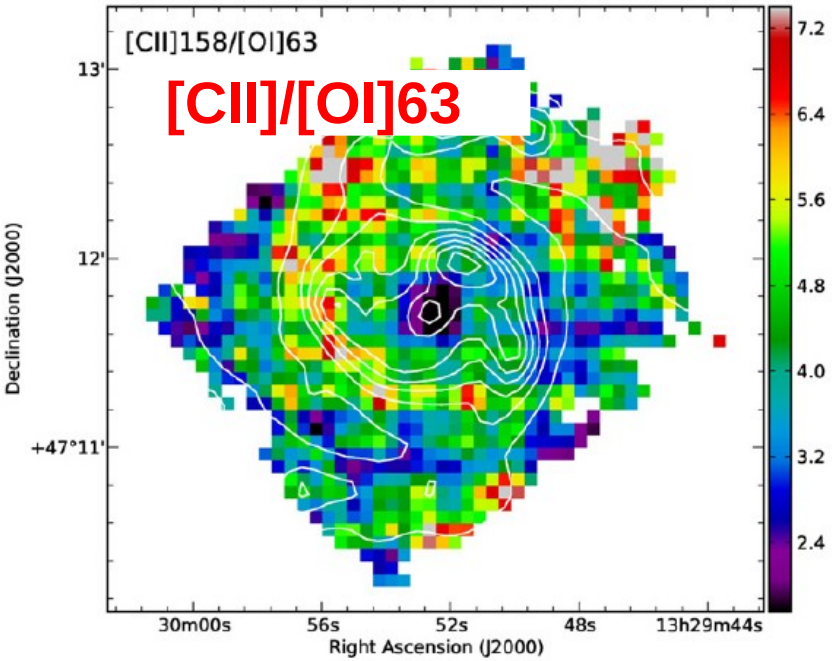


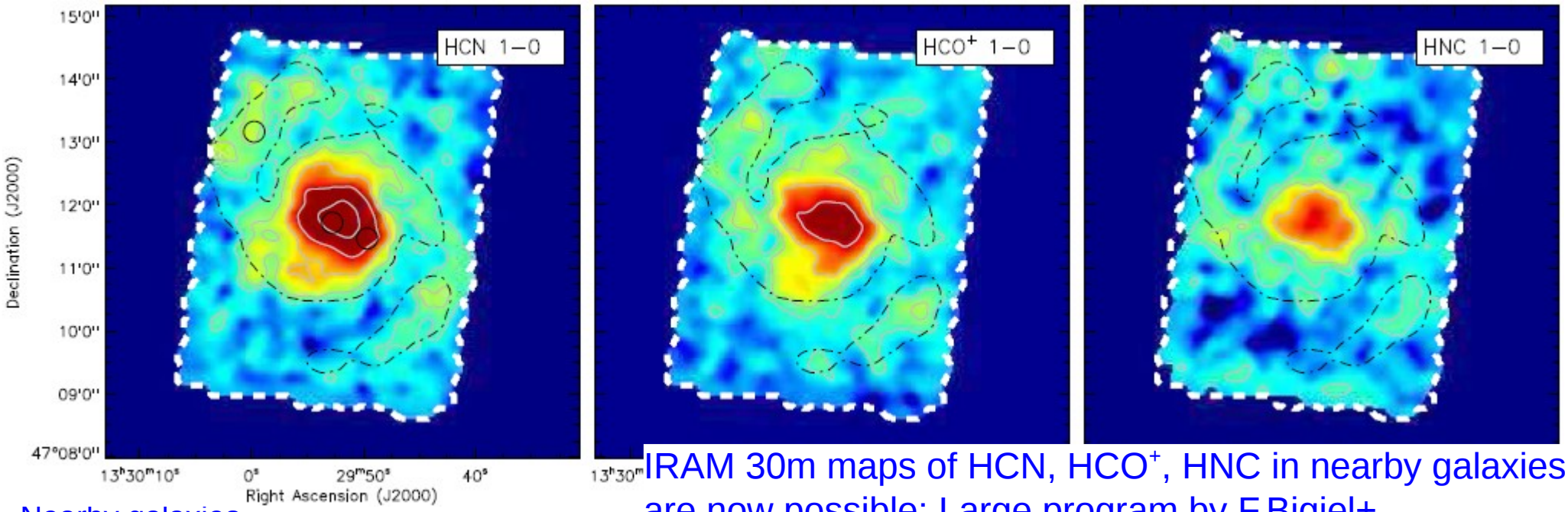
[CII]/[OI]63 ratio:

+ In general > 1
+ Varying strongly between 2 and 7
+ Lowest in the center where [OI]63 is strong – warm & dense gas
+ Highest in the inner part of the eastern spiral arm – cold & diffuse gas

Different regions of a galaxy: dense gas





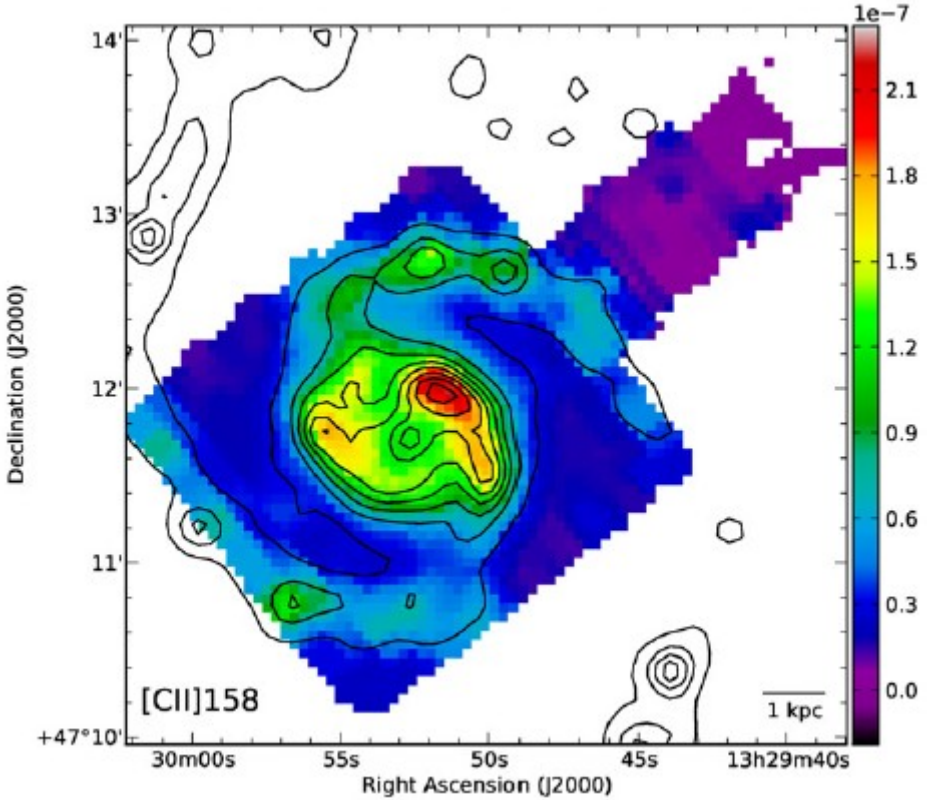


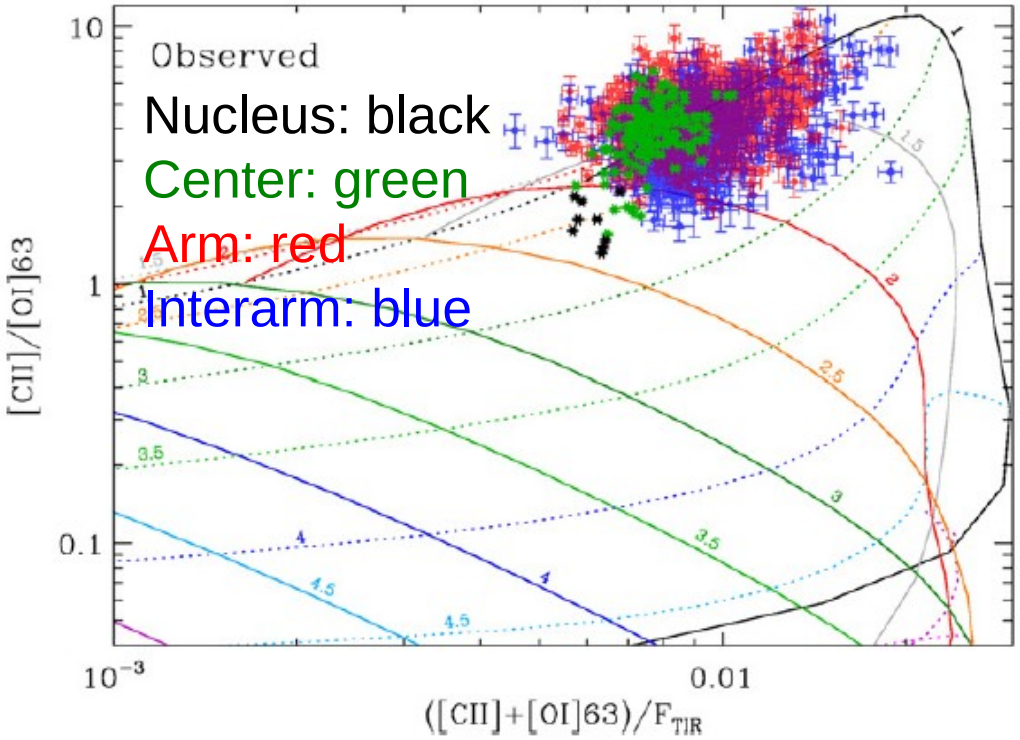
Nearby galaxies

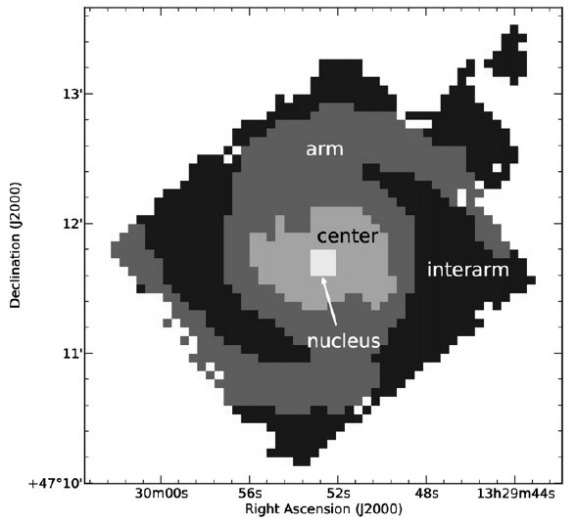
IRAM 30m maps of HCN, HCO^+, HNC in nearby galaxies are now possible: Large program by F.Bigiel+

Different regions of a galaxy: PDR models

M51 at 9.9 Mpc by Parkin+2013: PACS and SPIRE observations





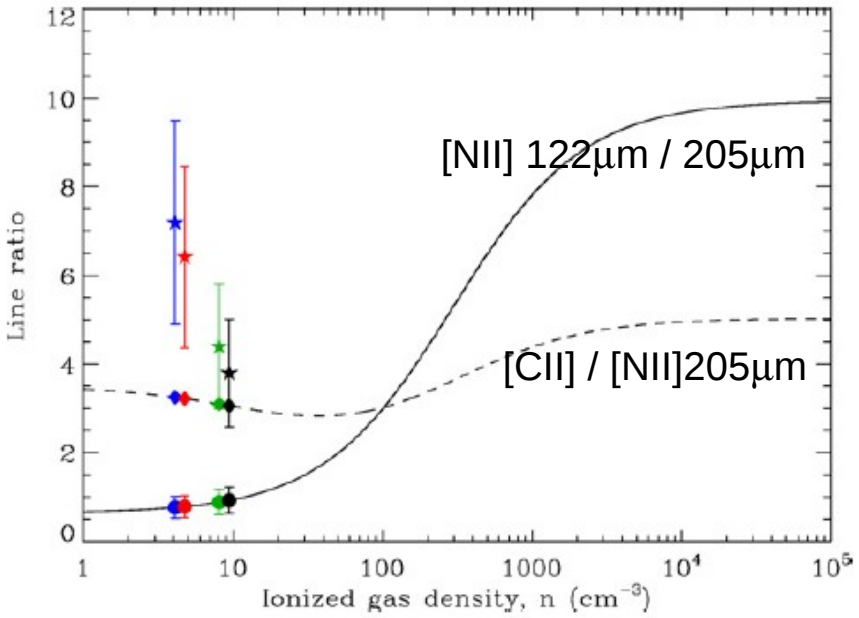


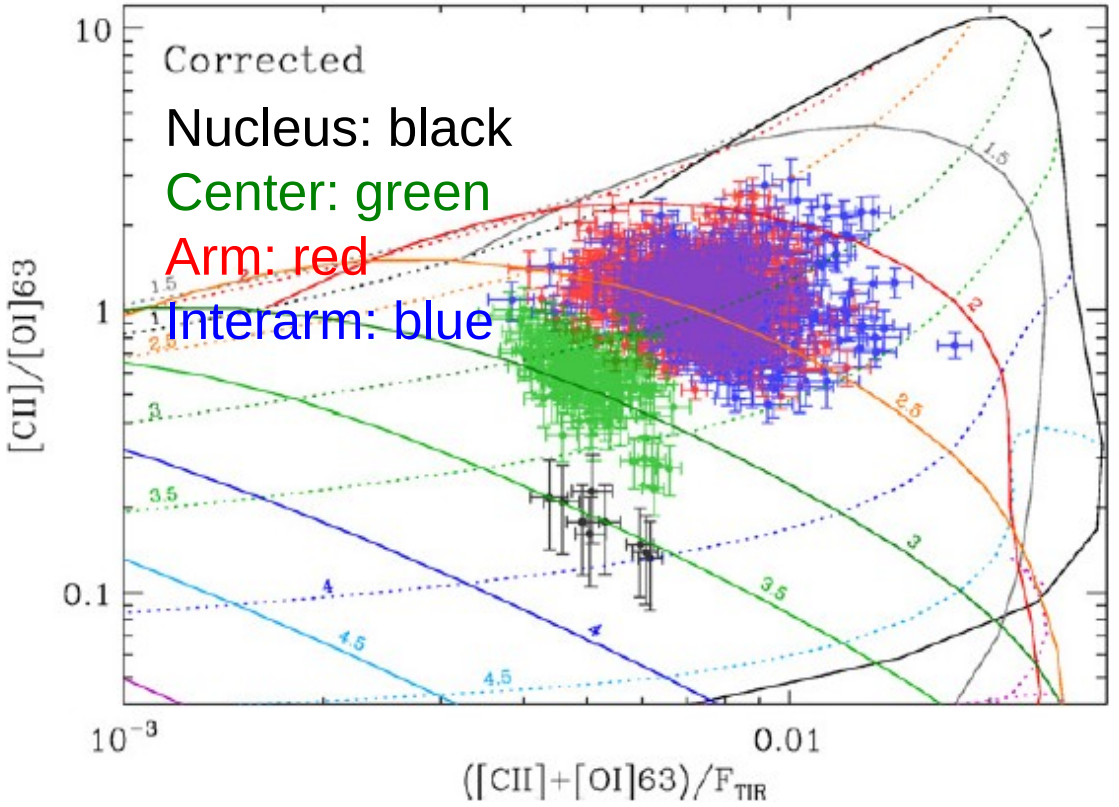
[CII]/[OI]63 > 1, ([CII]+[OI]63)/FIR ~ 1% (!!)

Models of Photon Dominated Regions (PDRs):
Dotted lines: log n, drawn lines: log G_0

PDR models indicate very low densities and FUV radiation fields or are not fitting at all !?!?

Correcting observed [CII] emission for $[CII]_{ionized}$





Observed [NII] 122/205
→ electron density
→ [CII]/[NII]205 from ionized gas
→ [CII] fraction from ionized gas

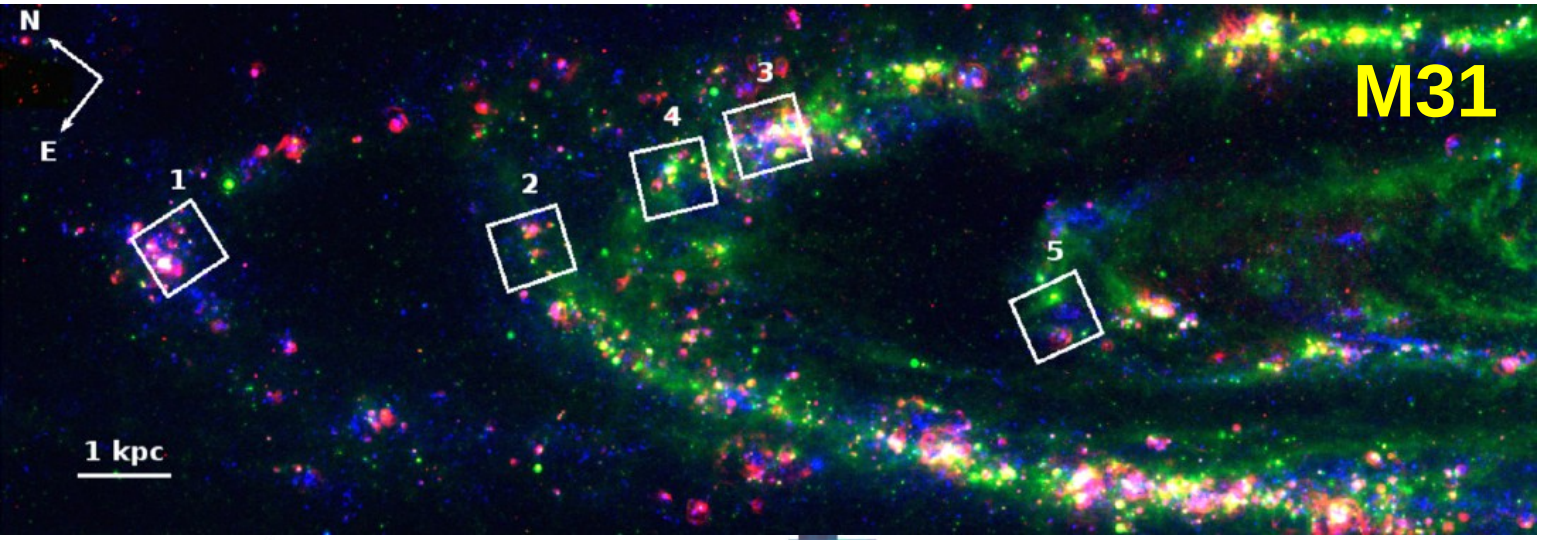
Nucleus: 80%
Center: 70%
Arm and interarm: 50%

Properties of the Gas Derived from the PDR Model

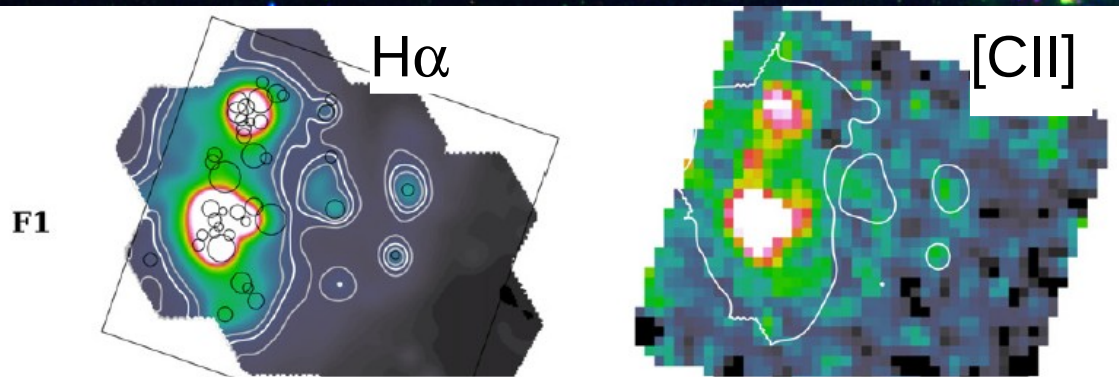
Case	Region	log (n/cm^{-3})	logG_0	T (K)
Corrected[b]	Nucleus	3.5–4.25	3.25–4.0	240–475
	Center	2.5–4.0	2.5–3.5	170–680
	Arms	2.0–3.75	1.75–3.0	100–760
	Interarm	2.25–3.75	1.5–3.0	80–550

M51 – Parkin+2013 (cf. Cen-A Parkin+2014)

[CII] vs. Star Formation: contribution by diffuse gas

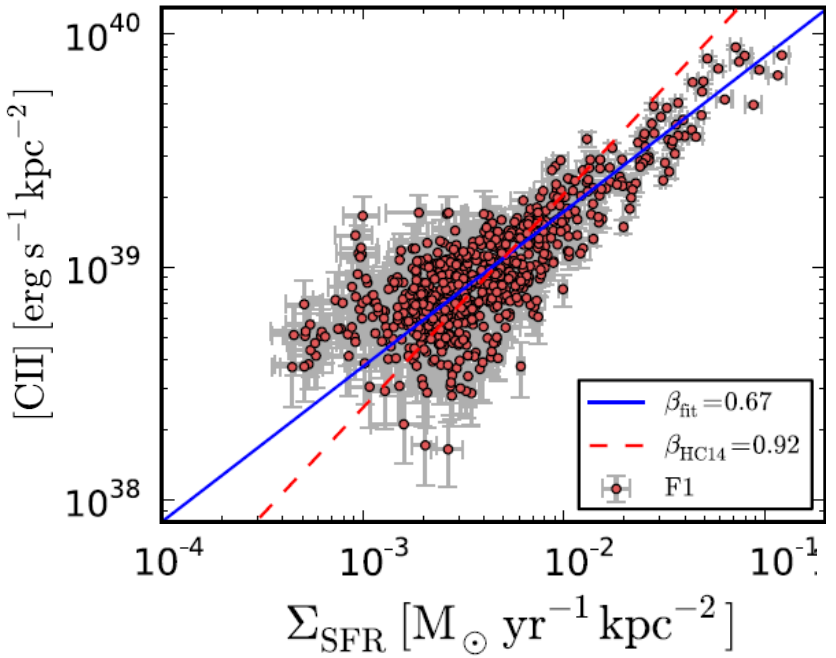


Blue: GALEX FUV,
Green: MIPS 24μm,
Red: Hα
by Kapala+2015



Decomposition into SF and diffuse regions:
L_0=4.2 x 10^{38} erg/s/kpc^2 **at 50pc resolution**.

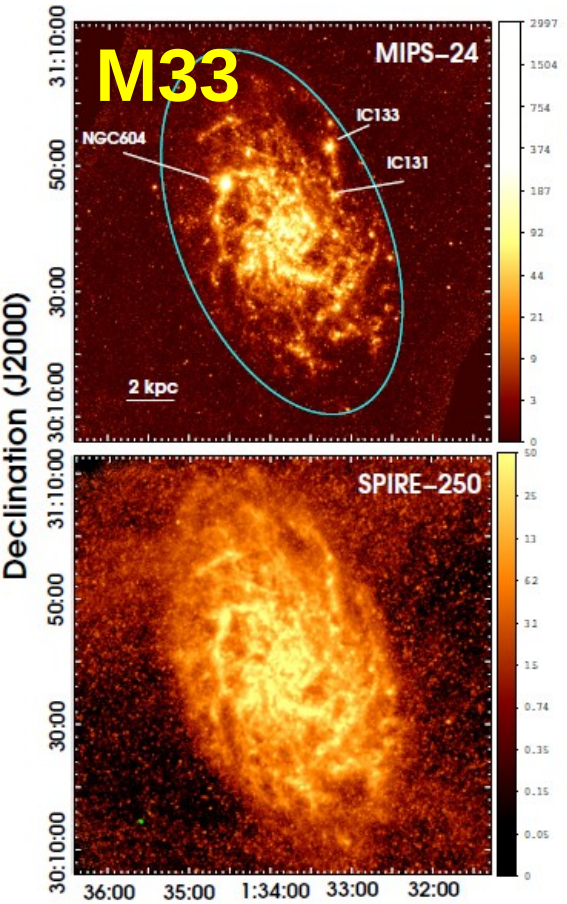
About 20% to 90% of [CII] emission come from outside star-forming regions.

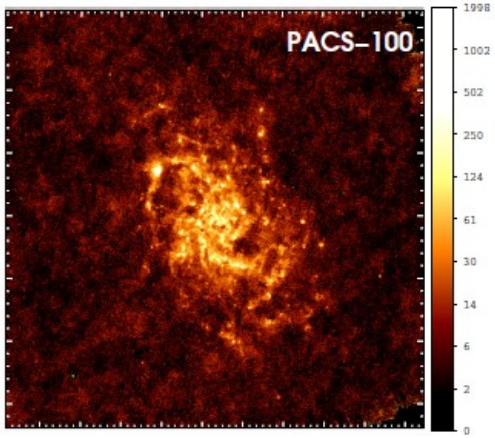


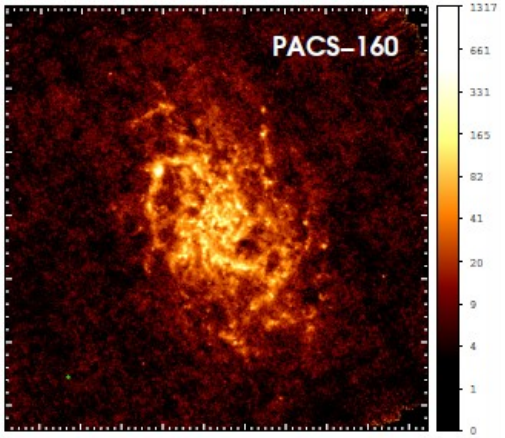
[CII]-SFR correlation holds also on 50pc scales, but with flatter slope (β_{fit}=0.67) than on large scales. Diffuse gas may be heated by a **diffuse UV field** from B-stars.

Total Infrared Continuum

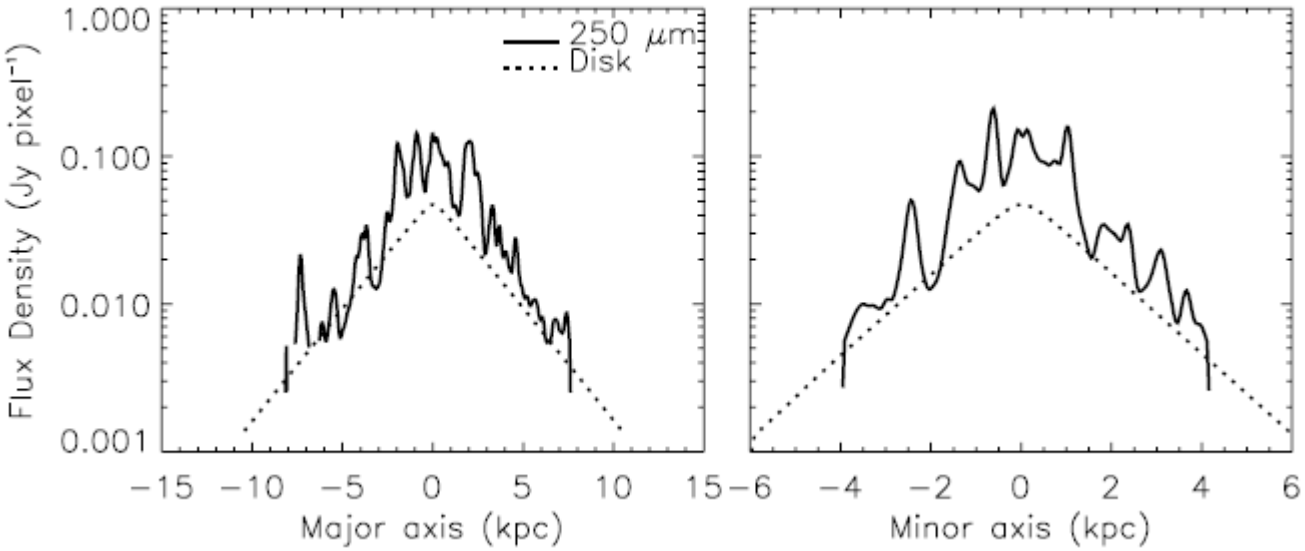
TIR – another tracer of Star Formation





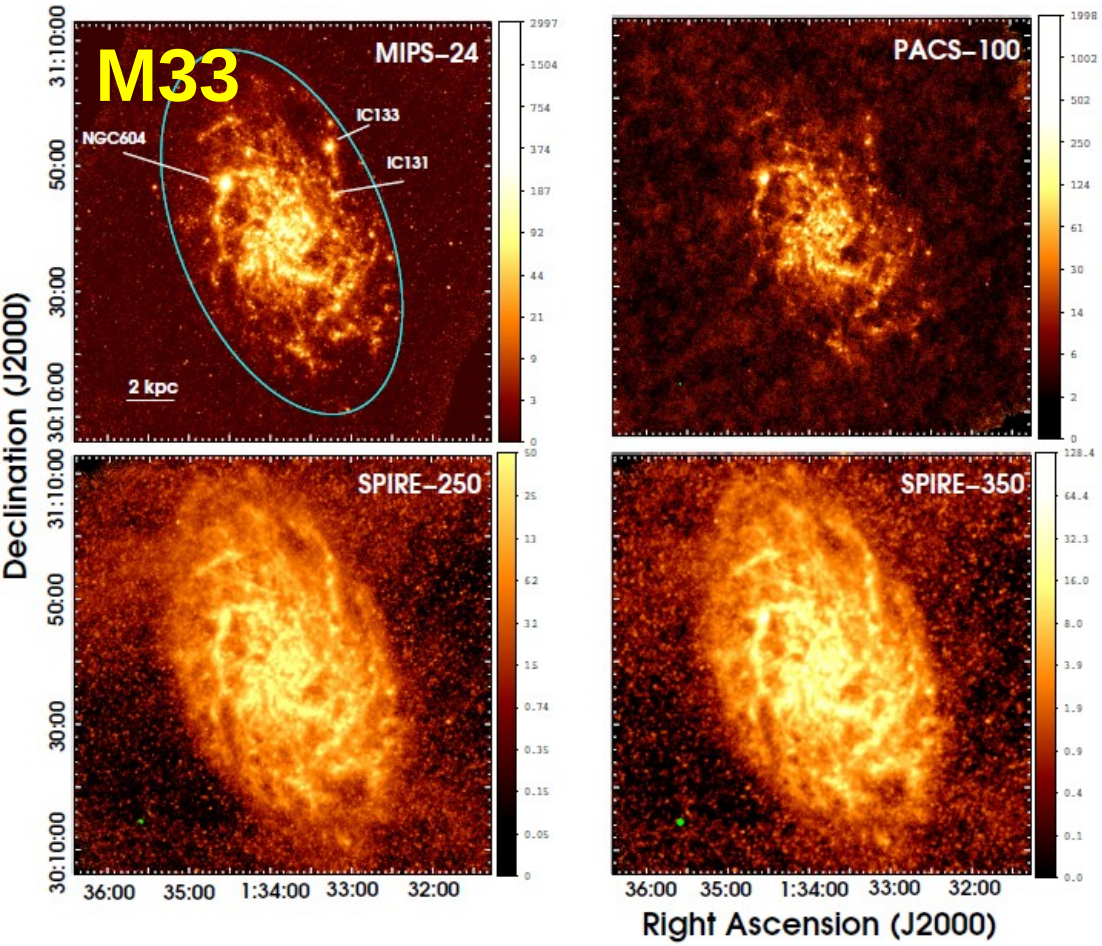


MIPS, PACS, SPIRE maps, HerM33es: Xilouris+2012; Boquien+2012, 2013, 2015

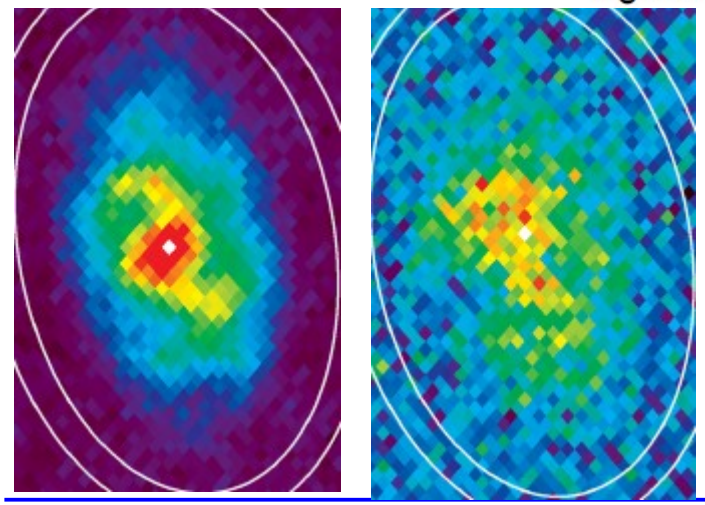


250μm profiles along major and minor axis with fitted exponential disk (dotted line), allowing separate analysis of spiral structure network. Xilouris+2015

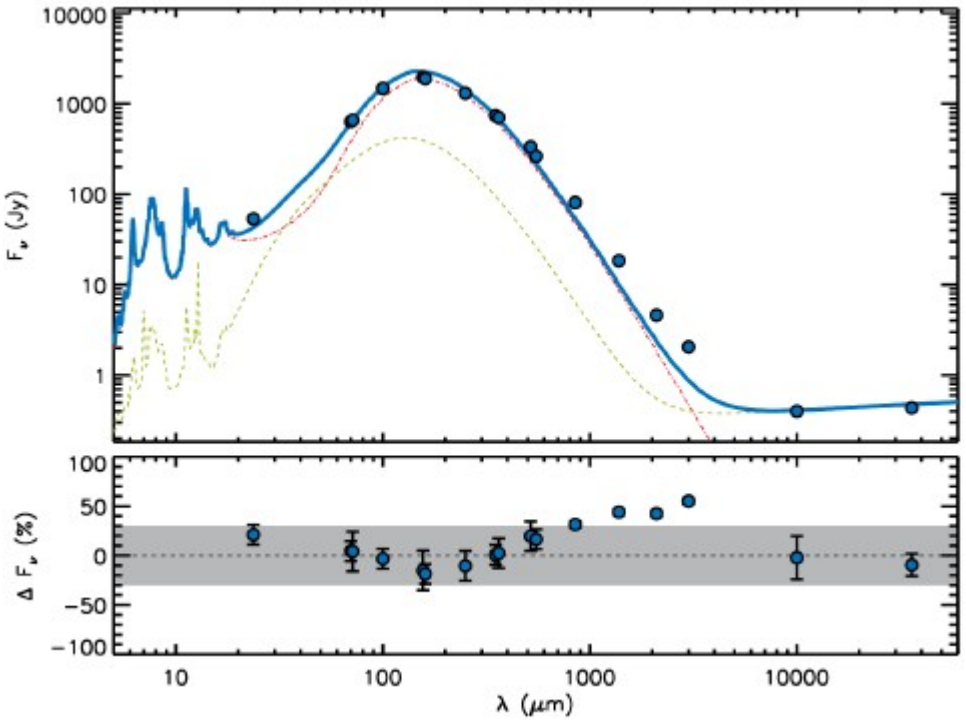
TIR – another tracer of Star Formation



MIPS, PACS, SPIRE maps, HerM33es: Xilouris+2012; Boquien+2012, 2013, 2015

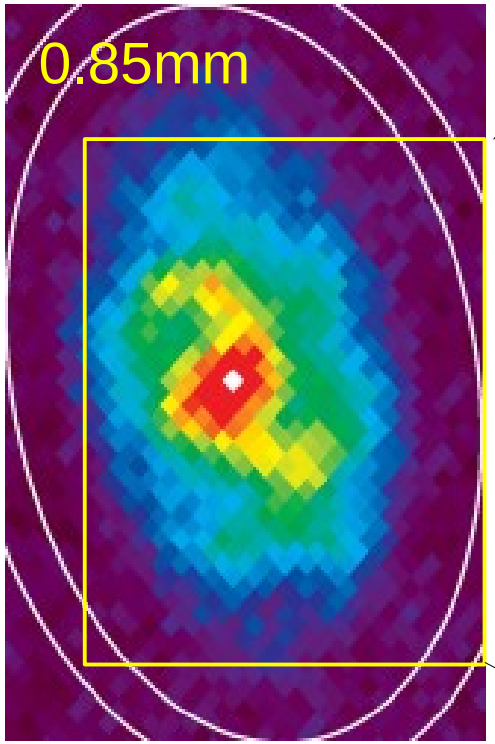


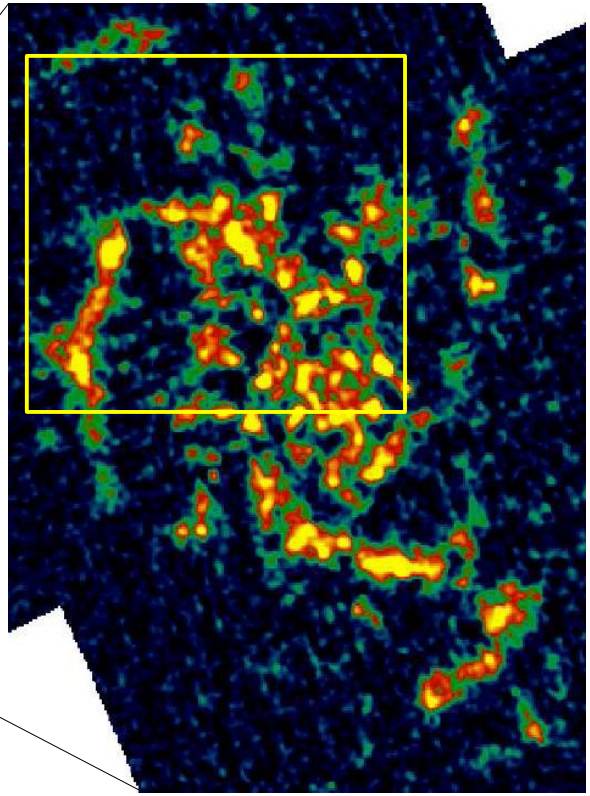
Planck at 850µm & 2.1mm (4.8' & 10' res.) Hermelo+ subm.



Global Spectral Energy Distribution (SED) of M33, Hermelo, Relano+ subm.

M33 at 0.85mm and 2mm

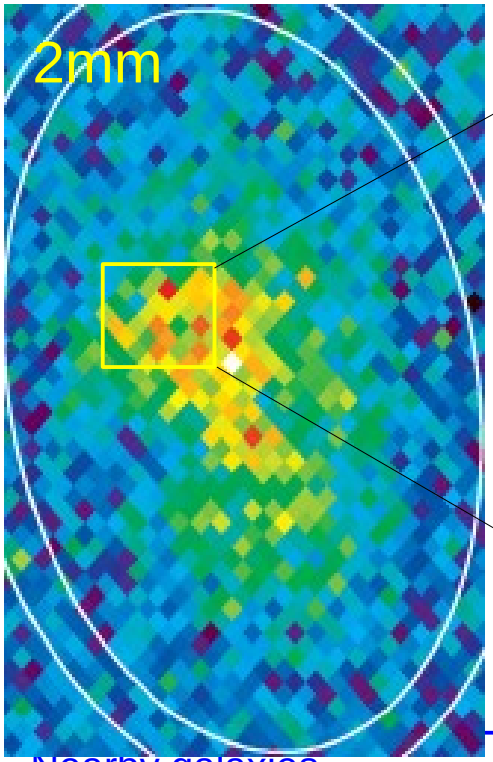


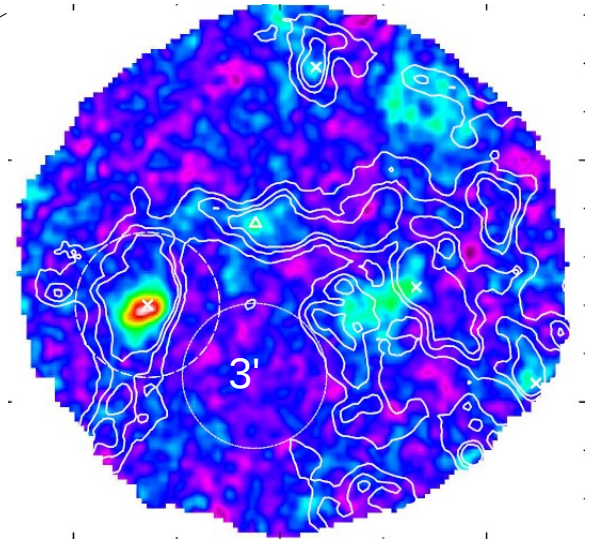


LABOCA/APEX map at
0.85mm (beam 20", 11' FoV)
by M.Albrecht

Spatial scales sampled by Planck overlap with the scales sampled by the next generation of large continuum cameras at IRAM-30m:

NIKA-2 / 30m will have 7.5' field-of-view for simultaneous observations at 2mm and at 1mm.

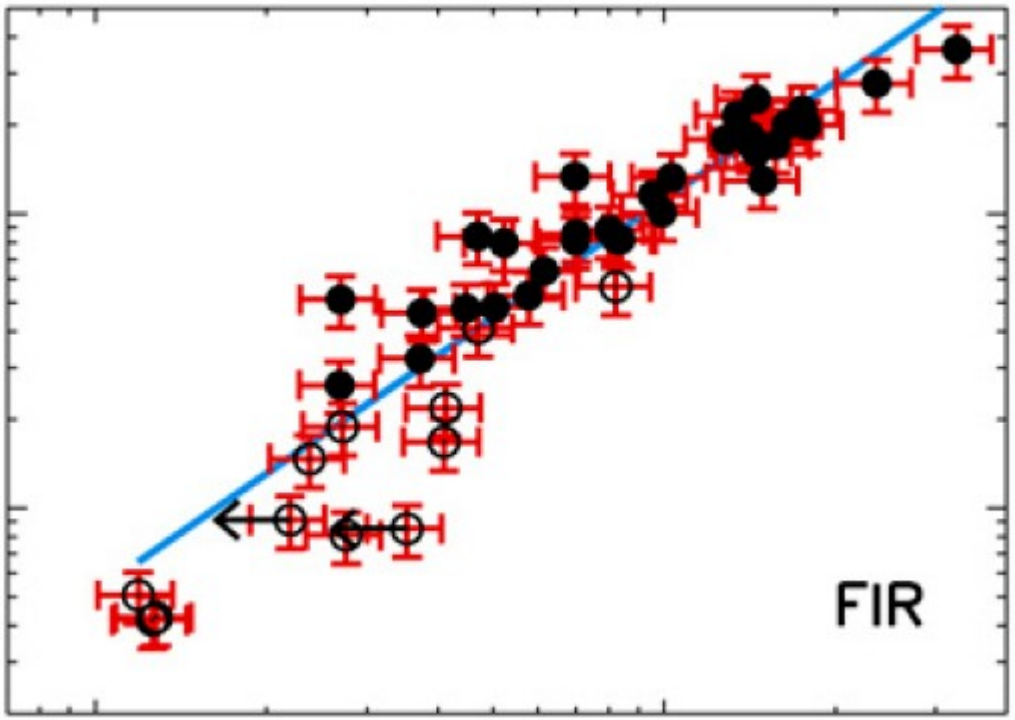




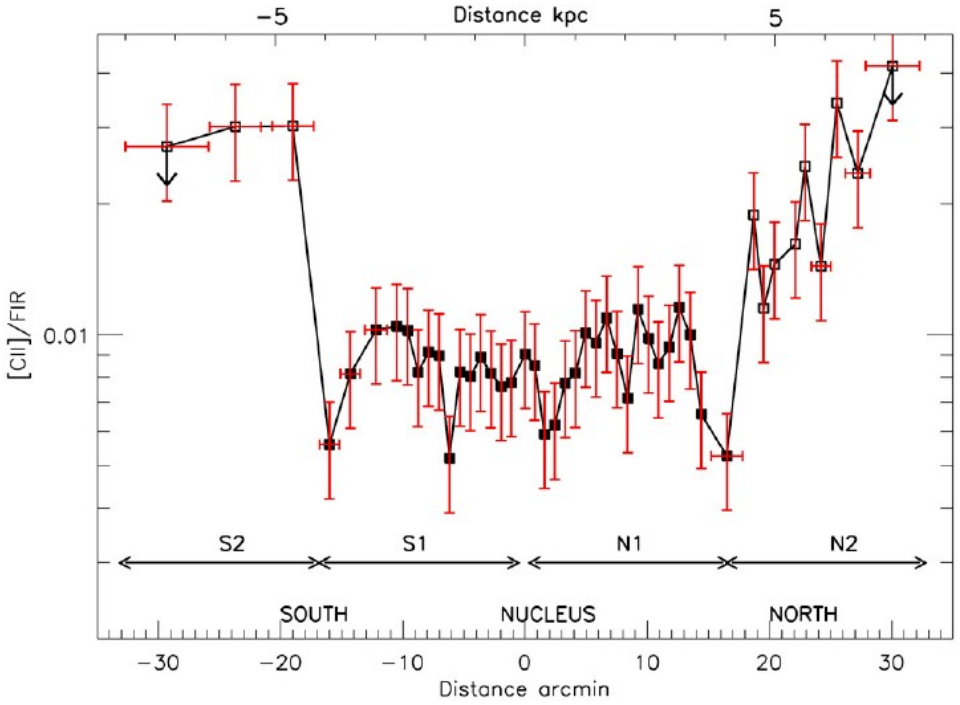
GISMO/IRAM-30m map at
2mm (beam 17", 1.8'x3.7' FoV)
with SPIRE 250µm contours
by Relano, Kramer+

Planck maps at 0.85mm & 2.1mm
(beam 4.8' and 10') Hermelo+ subm.

[CII]/TIR vs. Galacto-centric distance, R



FIR vs. [CII] along major axis of M33 at 280pc resolution, Kramer+2013

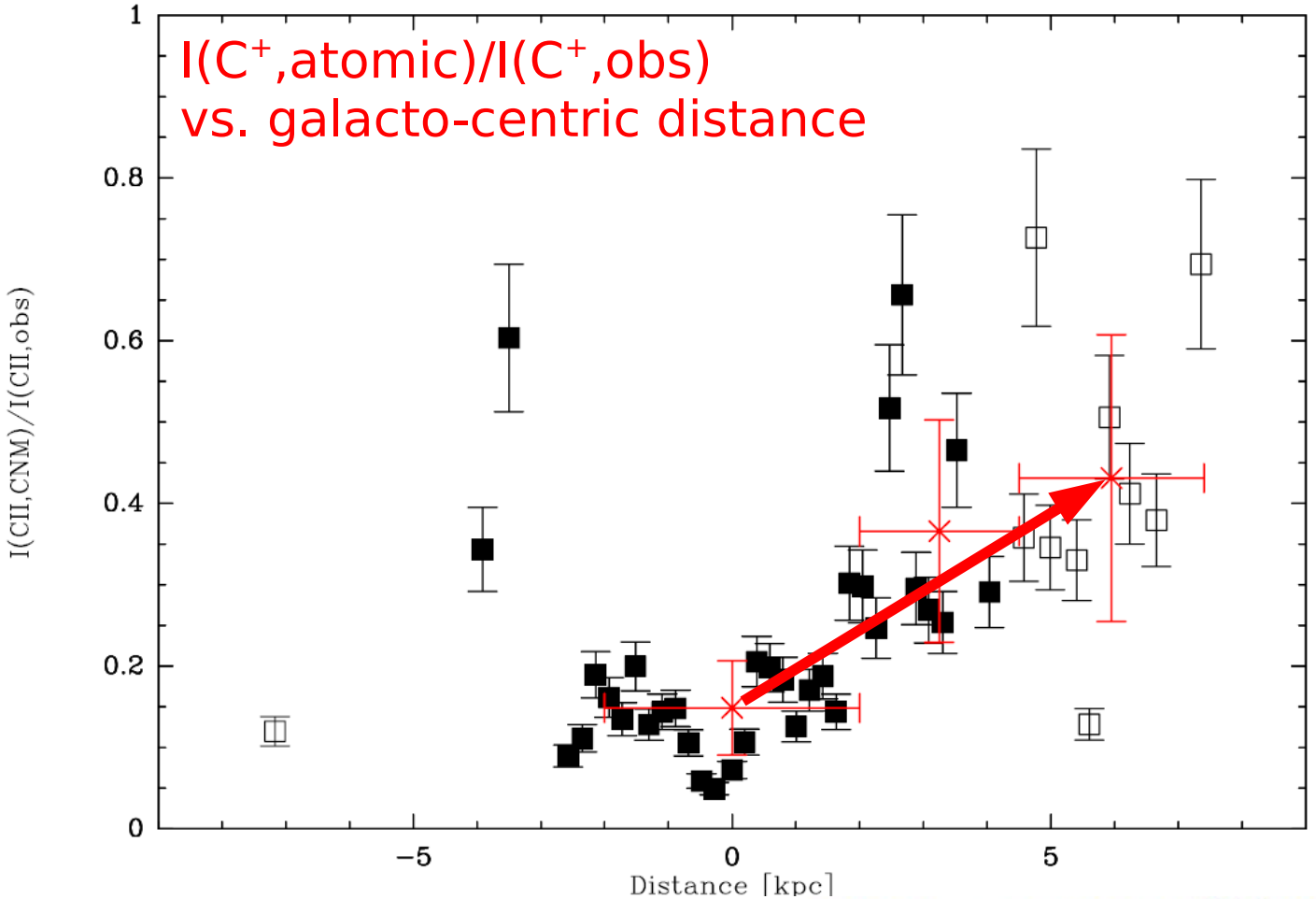


[CII]/FIR vs. radius.
[CII]/FIR increases from 0.7% in the inner 4kpc to up to 3% at 7kpc.

FIR and [CII] are tightly correlated (not surprisingly), but [CII]/TIR varies strongly, and rises with radius.

Possible causes of its **rise with radius**:
+ drop of average optical extinction, leading to increased [CII] zones
+ rising contribution of atomic gas (CNM) to [CII]
In M33, Metallicity gradient is only very shallow (Magrini+).

Fraction of [CII] emission from atomic gas: M33



40%

10%

Contribution of the atomic, cold neutral medium (CNM):

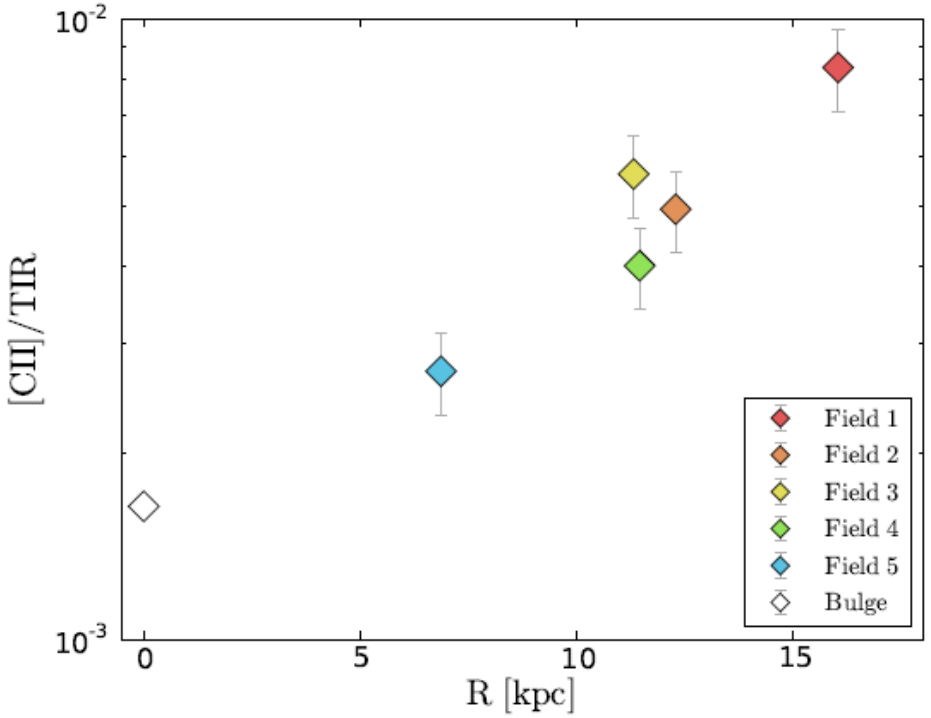
X_{C+}(CNM)=0.6 10^{-4}

T(CNM)=80K

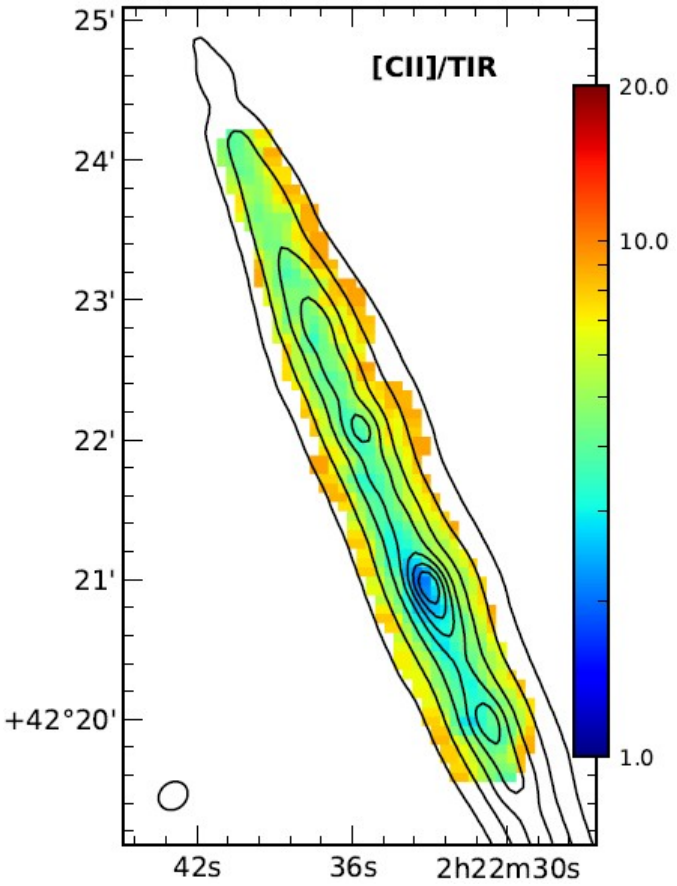
n(CNM)=100cm^{-3}

$$N(\mathrm{HI}) = 1.82 \times 10^{18}\, I'(\mathrm{HI})$$
$$N(\mathrm{HI,CNM}) = N(\mathrm{HI}) - N(\mathrm{HI,PDR})$$
$$N(\mathrm{C^+,CNM}) = X_{\mathrm{C^+}}\, N(\mathrm{HI,CNM})$$
$$I(\mathrm{C^+,CNM}) = 2.35 \times 10^{-21} N(\mathrm{C^+}) \times \left(\frac{2\,\exp(-\Delta E/T)}{1 + 2\,\exp(-\Delta E/T) + (n_{\mathrm{cr}}/n)} \right),$$

[CII]/TIR and dust-to-gas ratio



M31 at 700pc resolution, Kapala+2015



NGC891 at 600pc scale, Hughes+2014

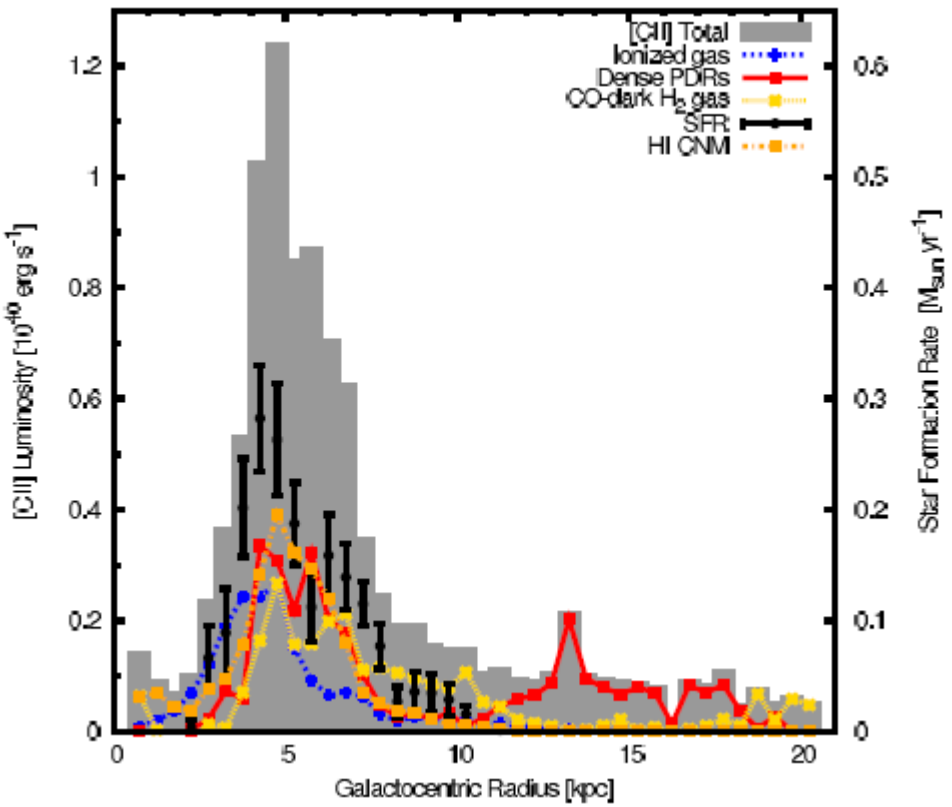
+ [CII]/TIR rise with radius found in M33, M31, NGC891 by factors up to 10
+ [CII] is linearly related with SFR on these scales

→ TIR drops with radius relative to [CII] and SFR.

In M31, decreasing metallicity leads to observed **drop of dust-to-gas ratio** (DGR, Draine+2014). FUV photons penetrate deeper into the molecular clouds. For the same Av, the [CII] flux is increased for the same amount of absorbed radiation, [CII]/TIR rises. (cf. Israel+1996).

Other effects: dust-extinction curve, star-formation history, hardness of radiation field

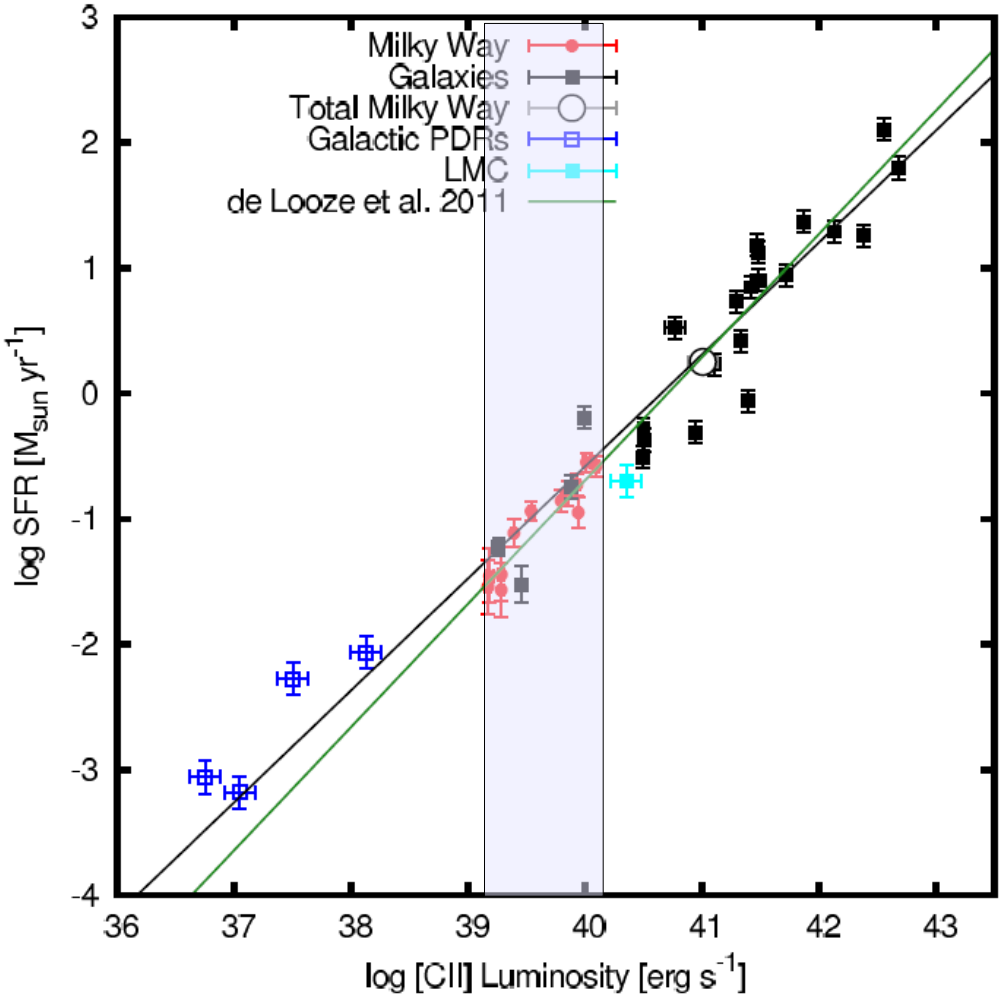
Contributions to the [CII] emission in the Milky Way



[CII] luminosity vs. Radius in the Milky Way, Pineda+2014

[CII] emission contributions:

+ 20% – diffuse, ionized gas
+ 25% – purely atomic gas
+ 25% – molecular gas, but CO-dark
+ 30% – molecular gas, bright in CO, PDRs

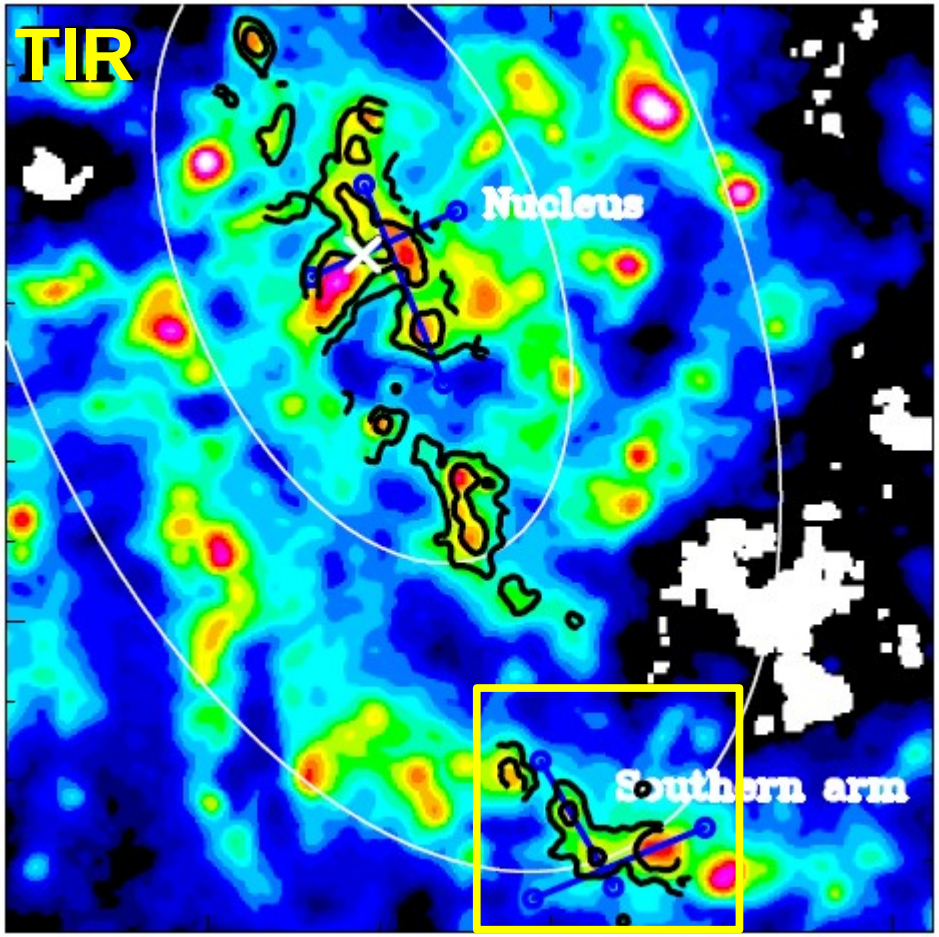


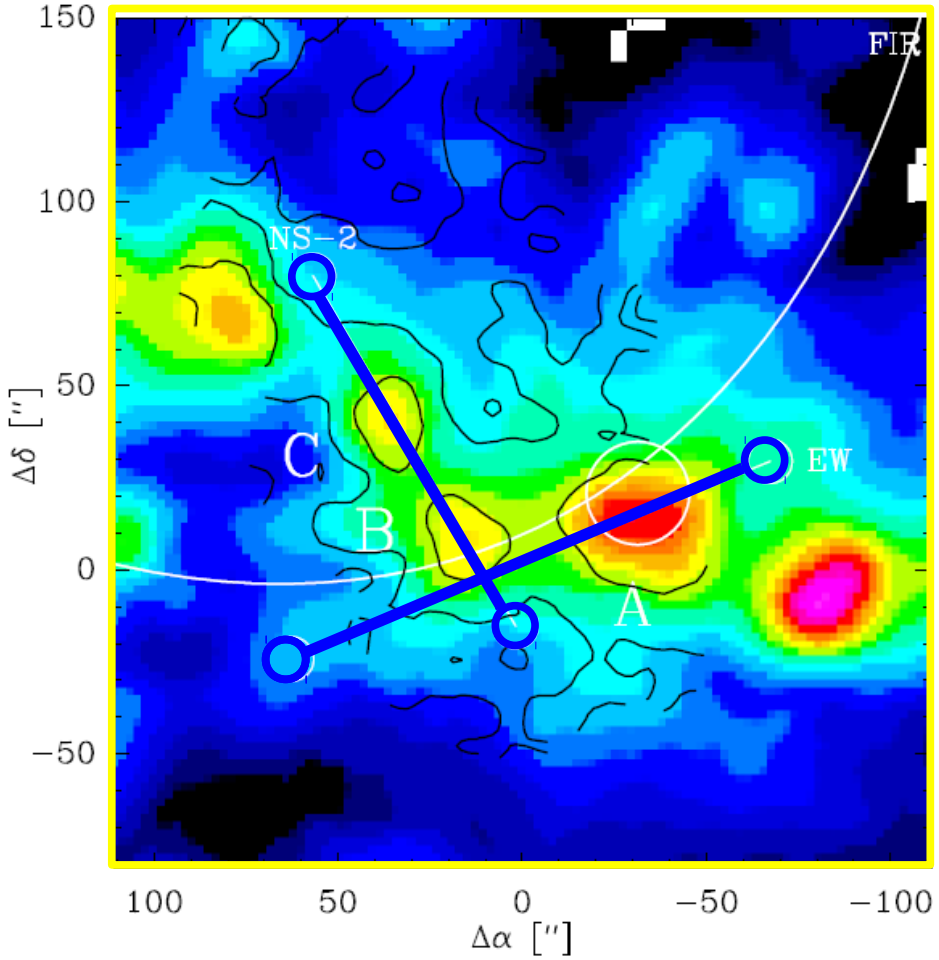
The Milky Way relation between [CII] and star formation agrees very well with the common law found in nearby galaxies over 6 orders of magnitude.

[CII] in general is emitted by a variety of different phases, none of them negligible !

[CII] in M33 at resolutions of 50pc and 2.6kms^{-1}

[CII] and TIR in M33



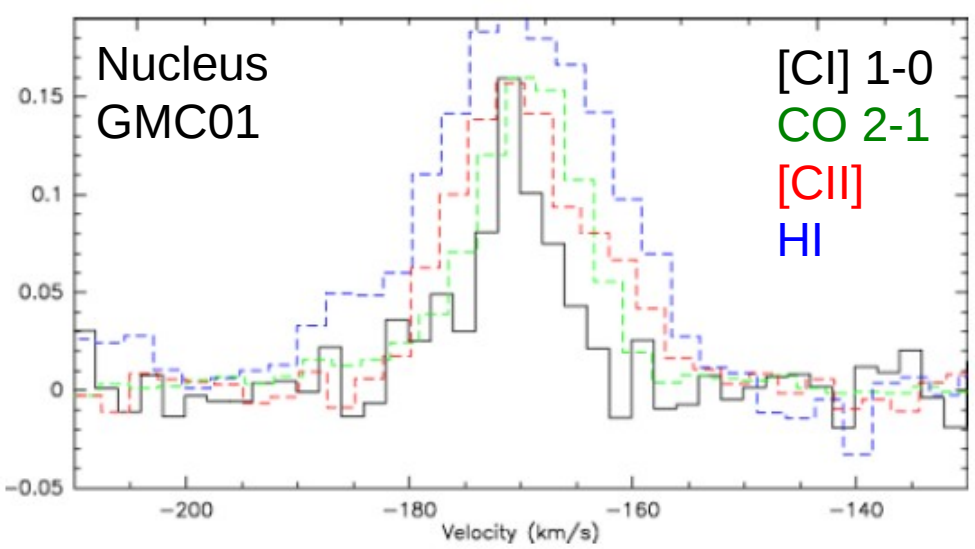


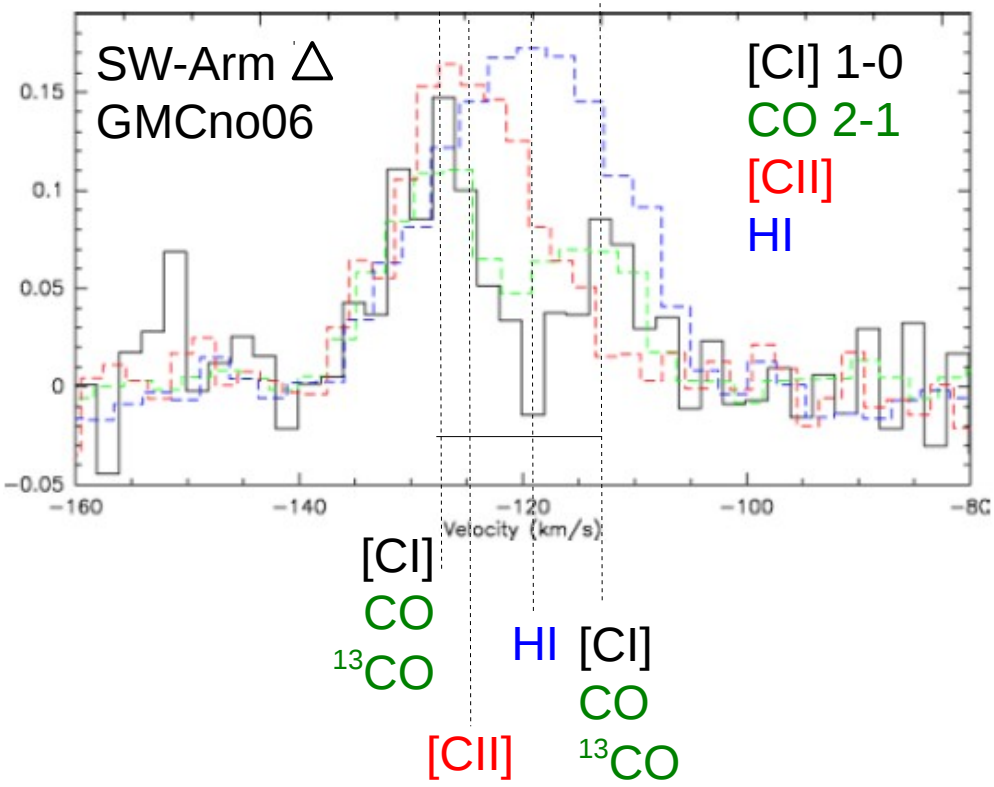
TIR continuum (colors) and PACS [CII] map (contours), HIFI [CII] cuts (blue lines). Ellipses mark radii of 1kpc and 2kpc.

Nikola+, Kramer+

Correlation between [CII] and the TIR continuum is tight, r=0.92, also on scales of 50pc.

C^+, C, CO, H Velocity structure at 50pc resolution





Nucleus: Similar line centroids

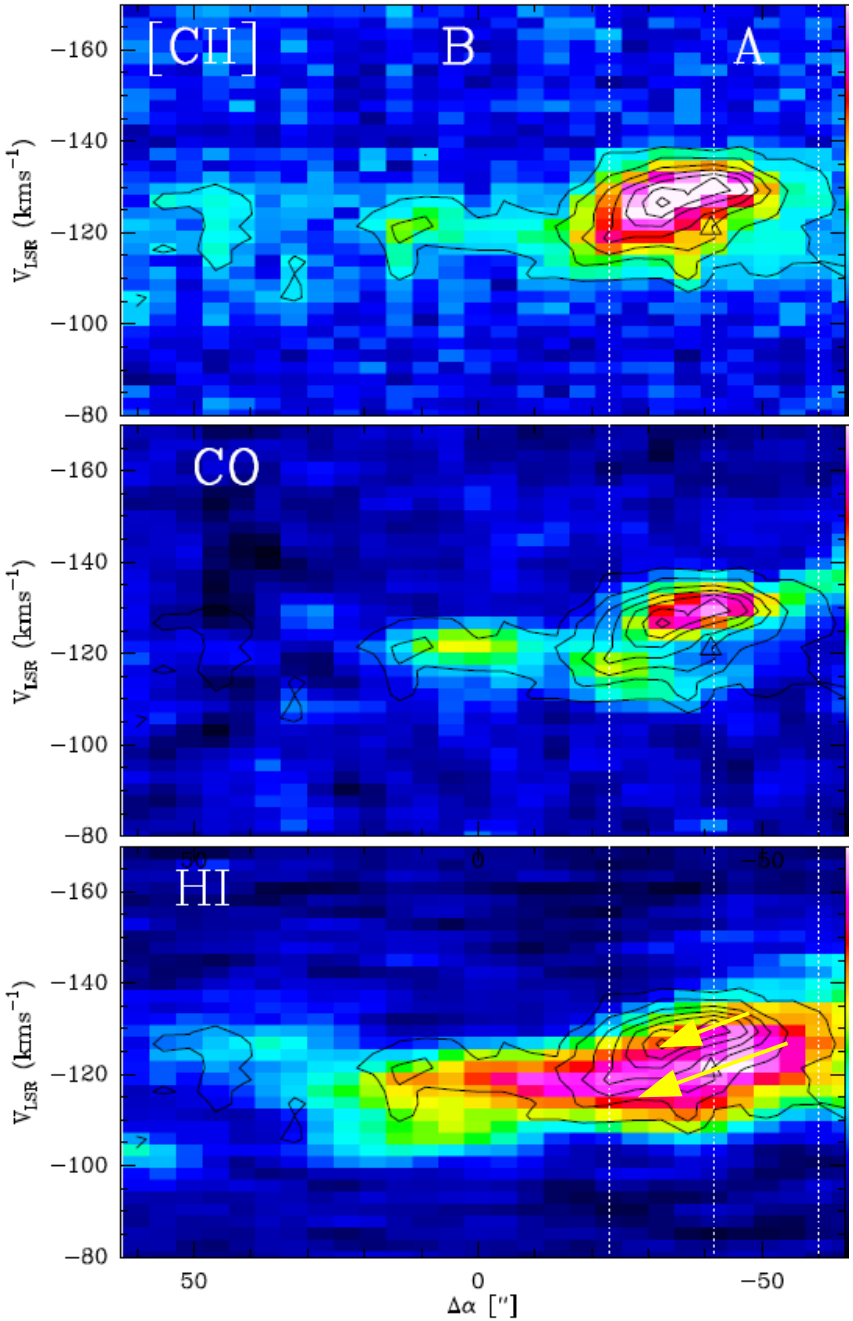
+ Strongly varying line widths: $\Delta v(C) < \Delta v(CO) < \Delta v(C^+) < \Delta v(HI)$ → thickness of gas disk

SW-Arm: Kinematical layering of emission

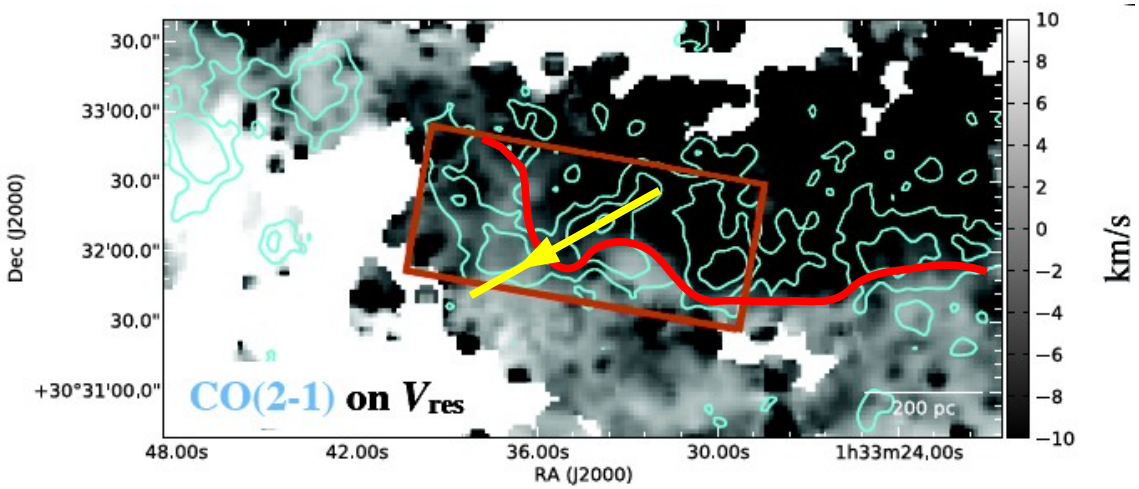
+ CO, ^{13}CO, and [CI] all trace two velocity components separated by ~15km/s
+ [CII] line centroid lies at +3 km/s and does not trace 2nd CO component.
+ HI line centroid lies at +5 km/s
+ Line ratios of [CI] / CO / [CII] / HI are strongly varying with velocity.

Glueck+ 2015 in prep. with [CI] 492GHz spectra from CSO and APEX.

Velocity structure II



Position-Velocity diagram along EW-cut through south-western arm of M33 (Kramer+)



CO contours on residual HI velocities, after correcting for the circular rotation, revealing spiral shock and streaming motions across the spiral arm. (Rosolowsky+)

Gas flowing through spiral shock causing piling-up of material, formation of H_2, and giant molecular clouds of ~10^6 M_{sun}, dense cores, and star formation. [CII] tracing formation of H_2.

Nearby Galaxies – FIR lines: Overview and Scope

The origin of [CII]

+ Going from scales of kpc to 50pc: integrated intensities

- **+ Dense ionized gas and small grains: Star formation rate**
- **+ Dense gas**
- **+ Diffuse ionized and neutral gas**
- **+ Dust: Total infrared continuum (TIR)**

+ Velocity information at 50pc

More on velocity information and on the effects of low metallicities in the next talks.

See also the poster on [CII] and [NII] 205μm spectra in IC342.

Next steps:

+ Deep FIFI-LS maps of dedicated regions and the outskirts.
  Requires careful selection of regions.
+ Follow-up upGREAT velocity resolved maps of [CII] and [OI] 63μm, [NII] 205μm