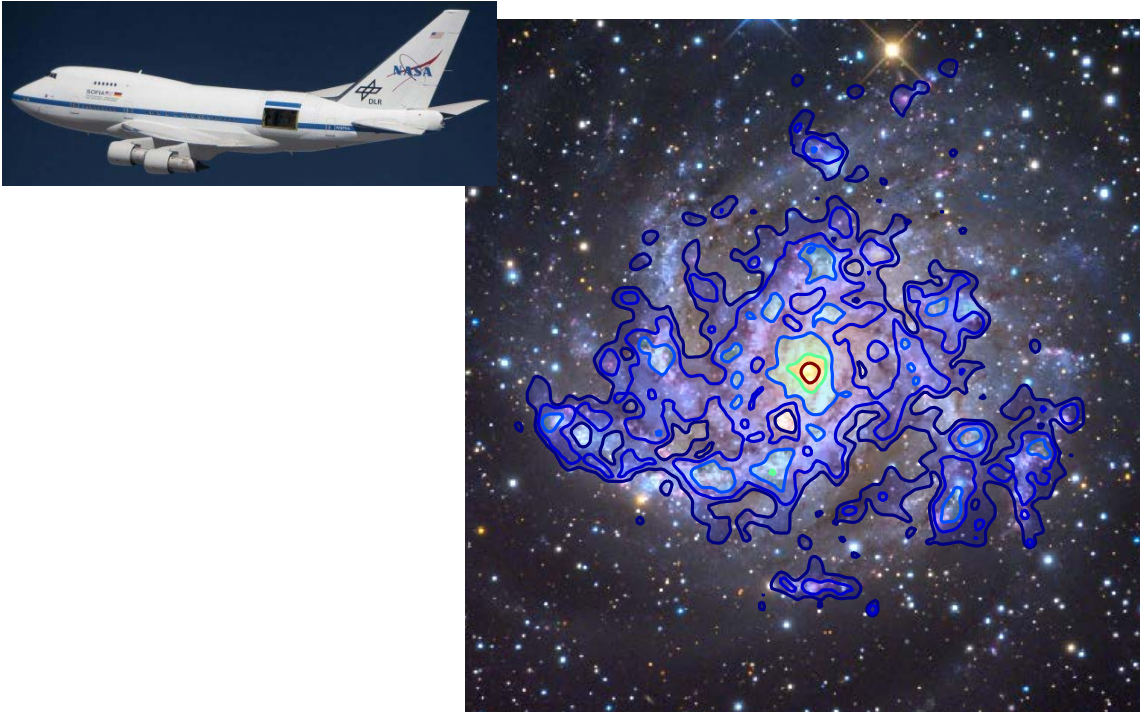


SOFIA/FIFI-LS CII observations of the nearby spiral galaxy NGC6946

February 24, 2021



Optical Image: LBT (Vincenzo Testa and Cristian DeSantis)

SOFIA/FIFI-LS CII Composite Image: Bigiel et al. 2020

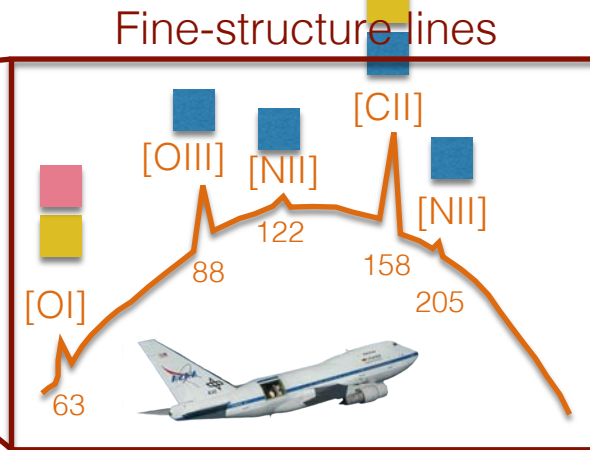
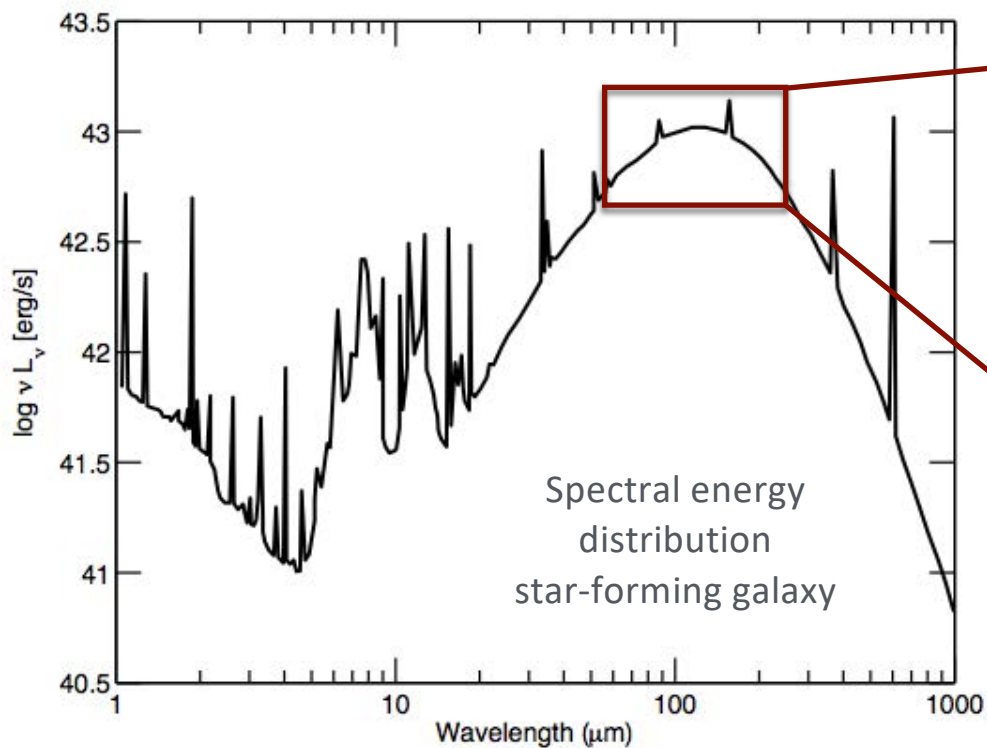
Frank Bigiel*

Argelander Institute for Astronomy

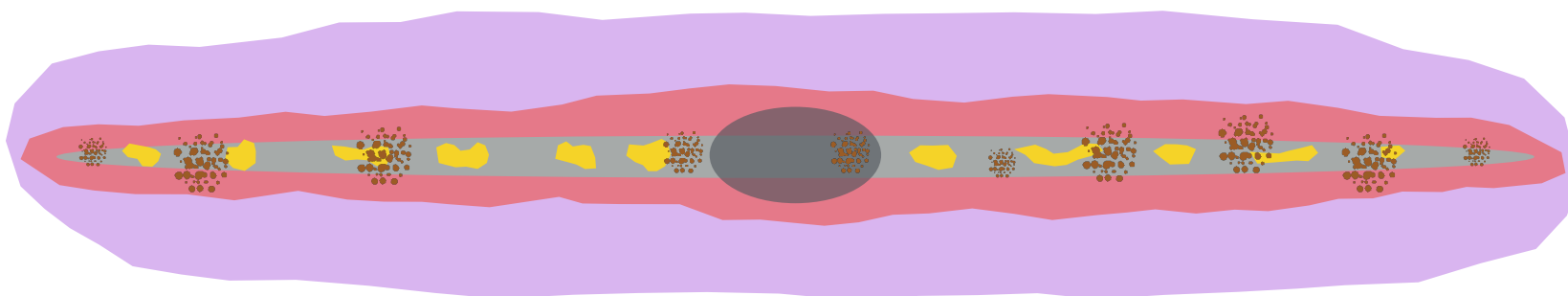
Univ. of Bonn

* on behalf of I. de Looze, A. Krabbe, D. Cormier, A. Barnes, C. Fischer, A. Bolatto, A. Bryant, S. Colditz, N. Geis, R. Herrera-Camus, C. Iserlohe, R. Klein, A. Leroy, H. Linz, L. Looney, S. Madden, A. Poglitsch, J. Stutzki, W. Vacca & FIFI-LS Science Team

FIR Spectral Lines and the Multiphase ISM



ALMA
 $z > 1.5$



Hot Ionized Medium

Warm Neutral Medium

Cold Neutral Medium

HII gas

Molecular gas

Dust

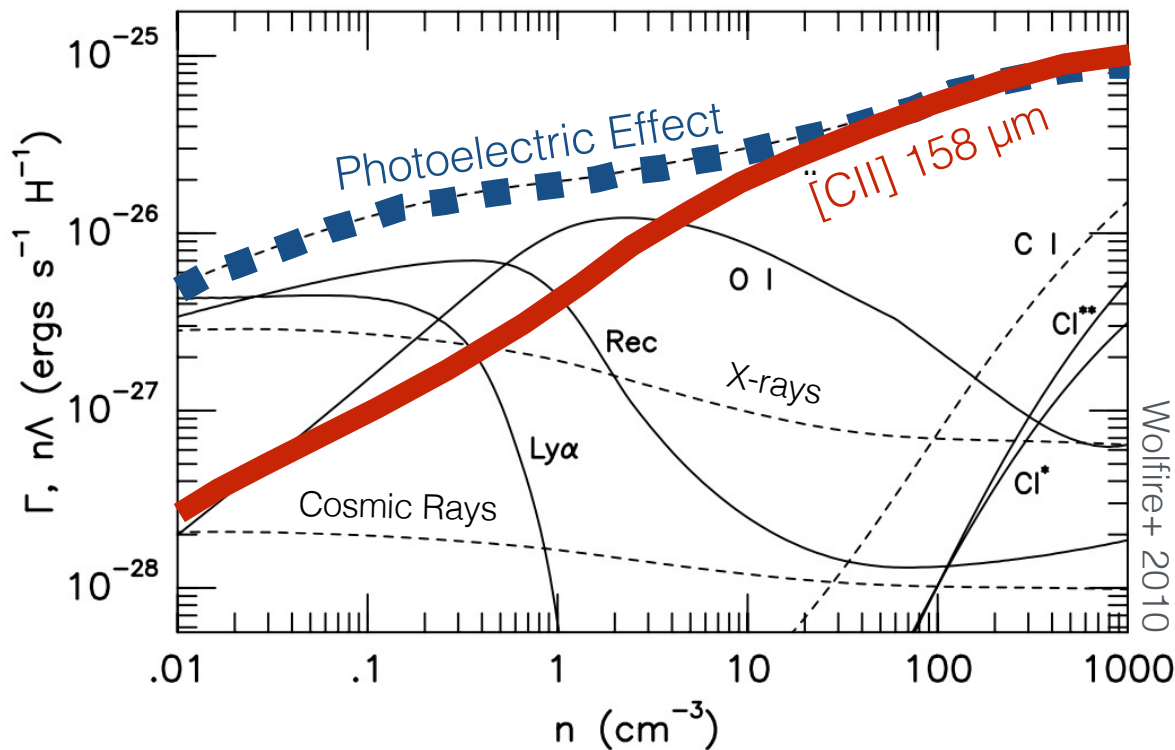
Motivation - CII as a Star Formation Rate Tracer

Heating (Γ) and Cooling ($n\Lambda$) of the ISM



WNM

CNM

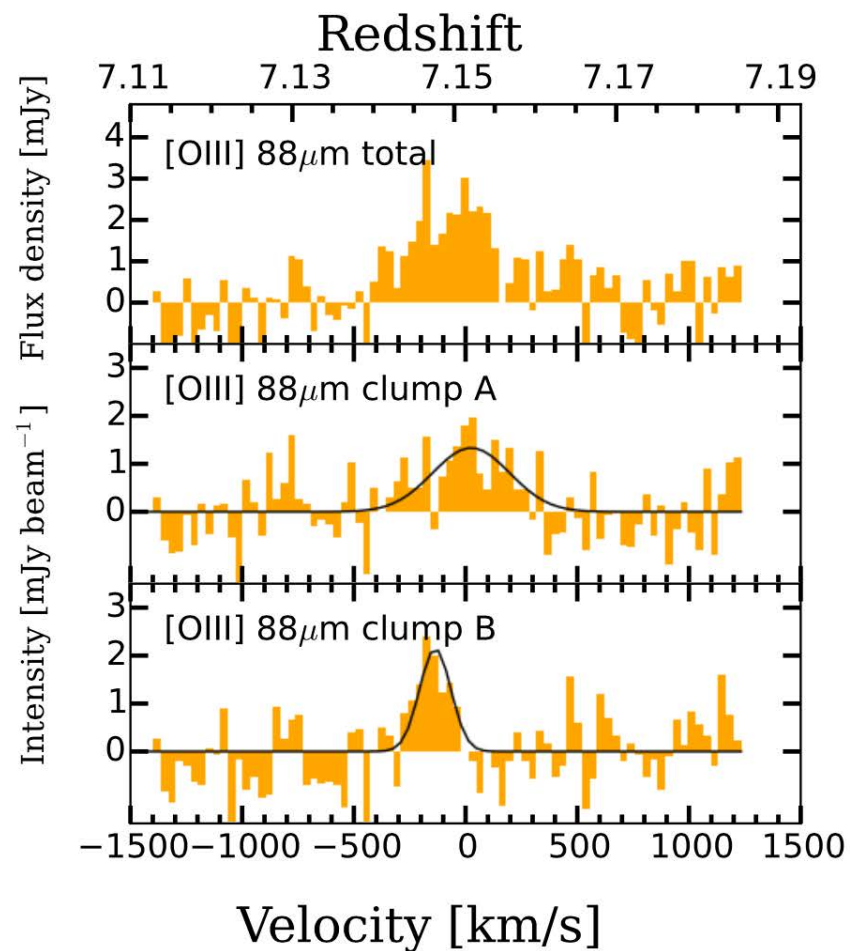
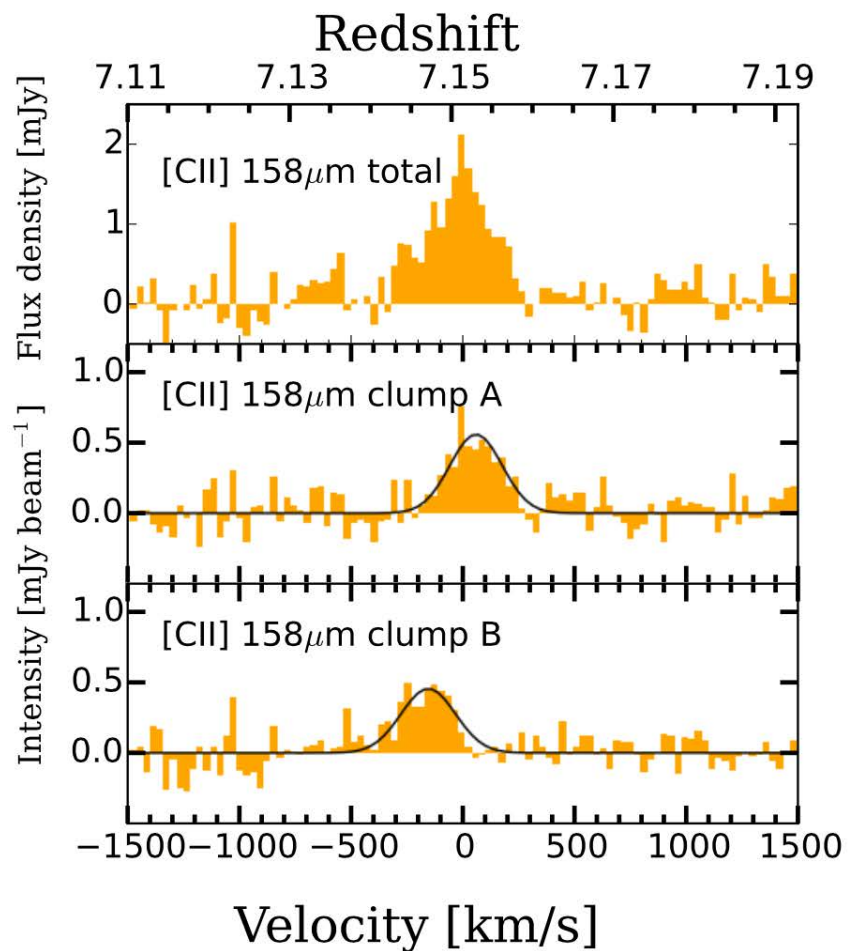


If the gas is in thermal balance

heating \approx cooling
 (star formation) ([CII])

Wolfire+ 2010

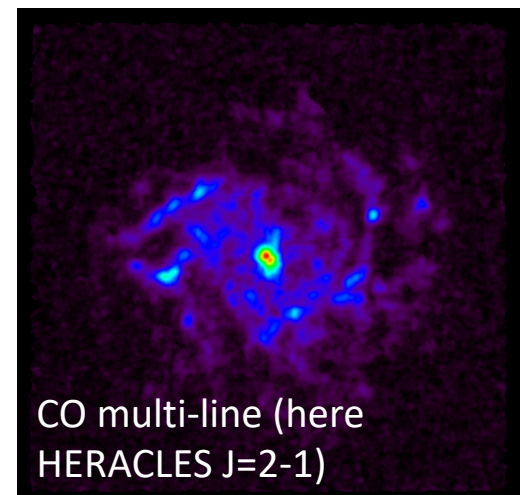
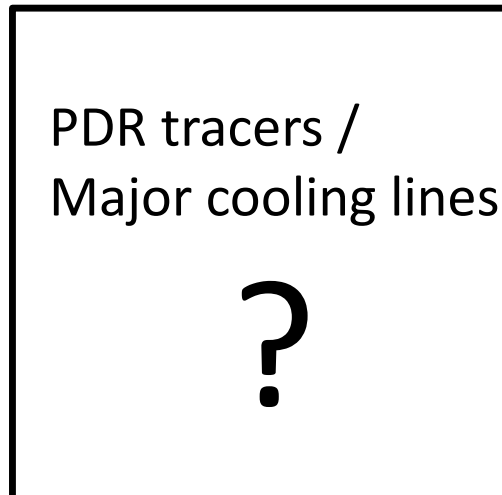
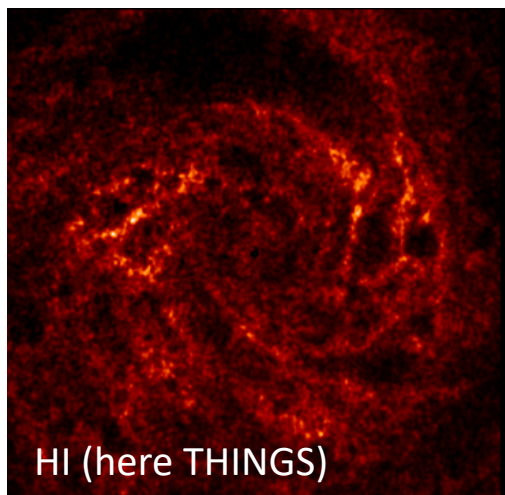
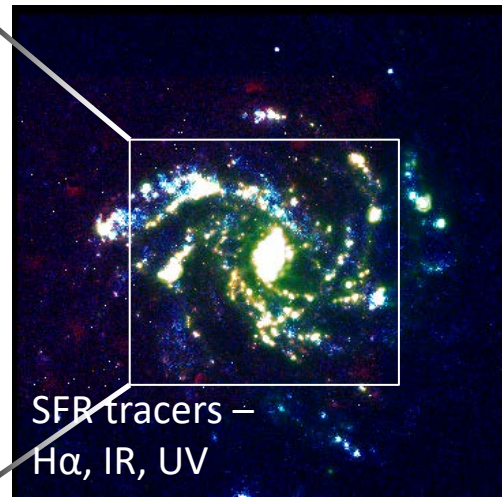
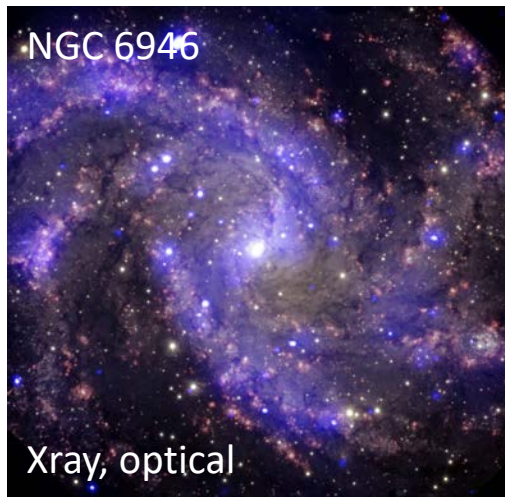
Motivation – High-z



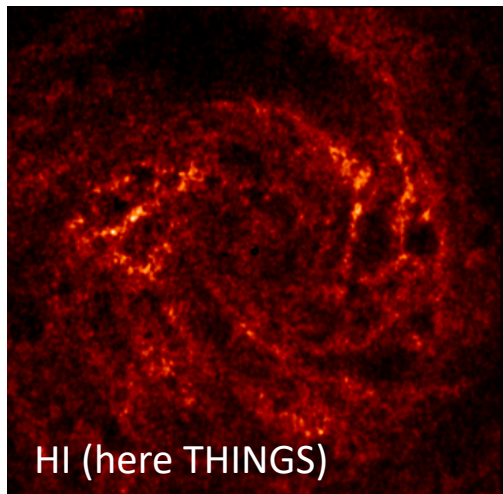
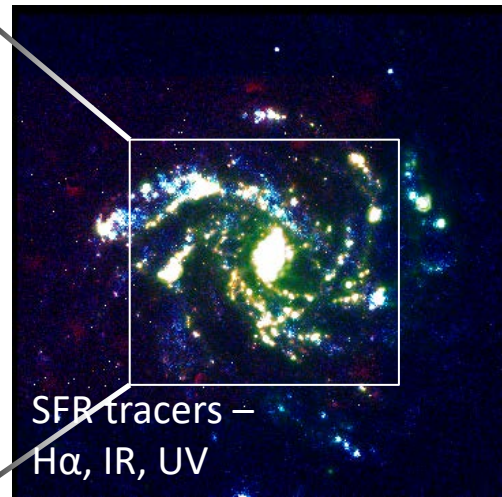
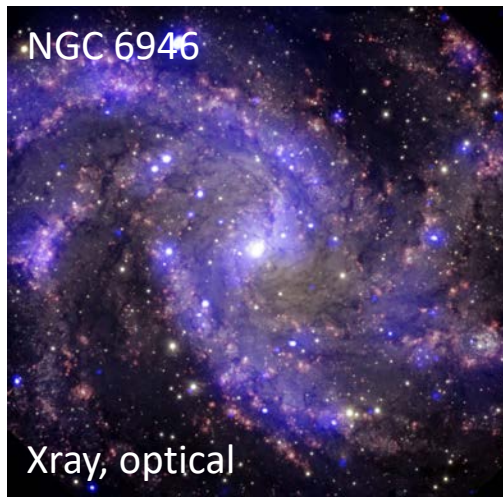
Hashimoto+ 2019

$z \sim 7$ Ly-break galaxy in ~ 40 min with ALMA!

Motivation - Why Full-Disk Nearby Galaxy Mapping? ...



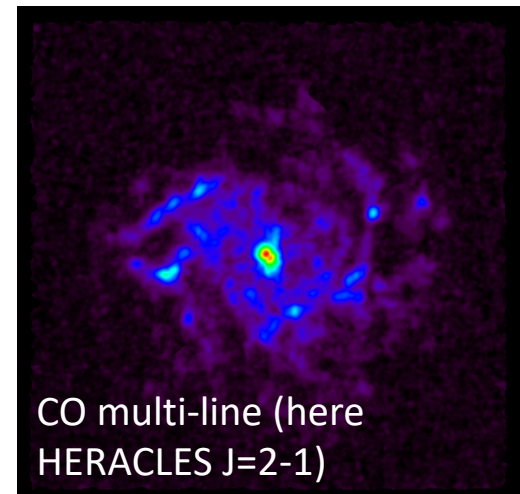
...to Fill the Gap of "Whole Galaxy", FIR Spectral Line Data



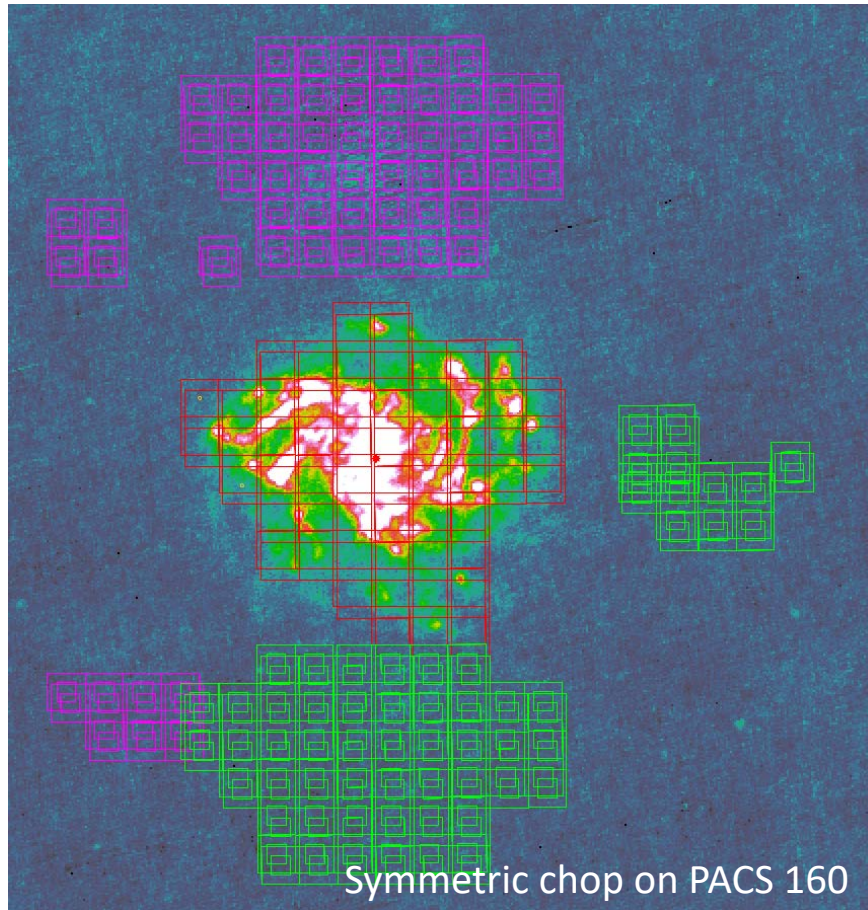
M51 (Pineda+ 2018,2020)

NGC6946 FIFI-LS (this work)

SOFIA/upGREAT large
program
(PI: A. Bolatto)



Full-Disk CII Mapping of NGC6946 with FIFI-LS

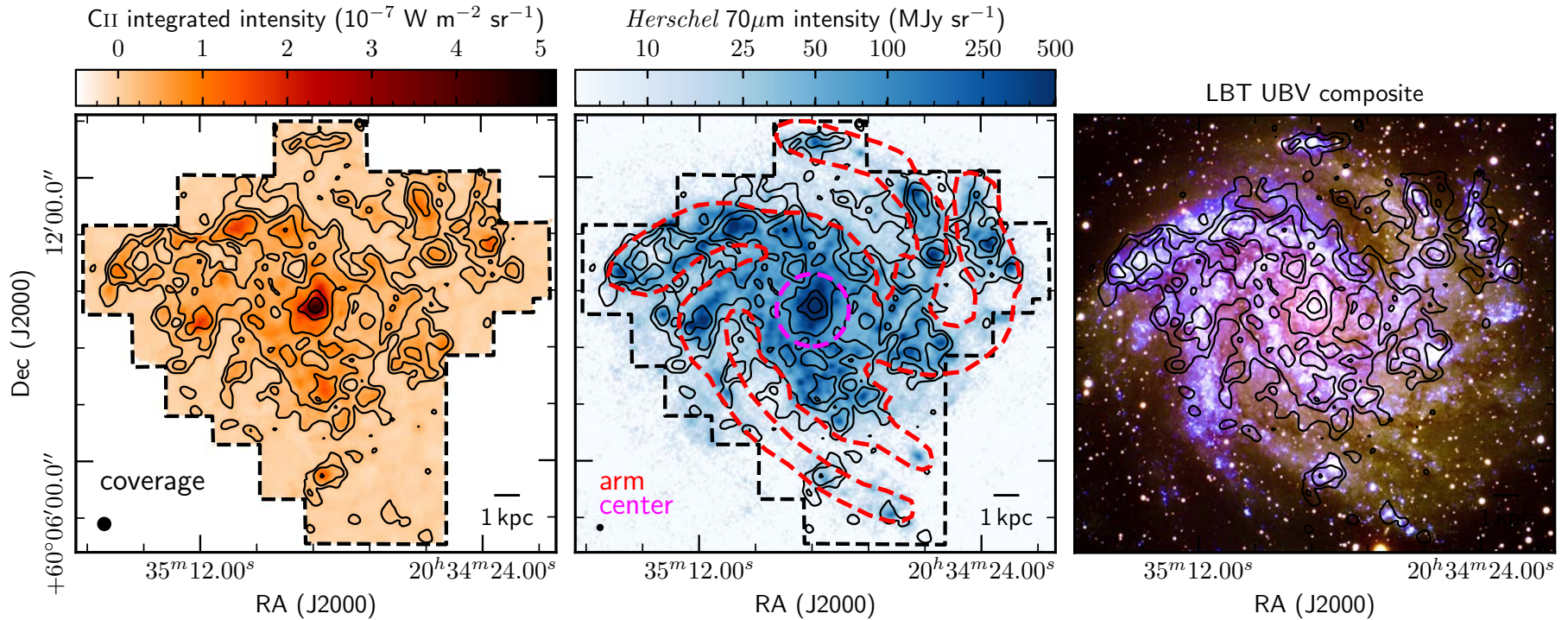


- NGC 6946 very molecular gas rich ($M_{\text{H}_2} \sim 10^{9.6} M_{\text{sol}}$!) and extended, actively star forming (SFR $\sim 3 M_{\text{sol}}/\text{yr}$) nearby ($\sim 7.7 \text{Mpc}$) late-type disk
- Wide-field mapping of entire molecular star forming disk in 10 h at $16''$ res.
- Observed 56 fields (dithered) during 3 flight series 2015 - 2016

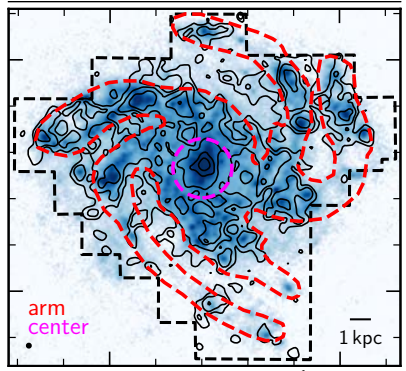
Science Team:

I. de Looze, A. Krabbe, D. Cormier, A. Barnes, C. Fischer, A. Bolatto, A. Bryant, S. Colditz, N. Geis, R. Herrera-Camus, C. Iserlohe, R. Klein, A. Leroy, H. Linz, L. Looney, S. Madden, A. Poglitsch, J. Stutzki, W. Vacca & FIFI-LS Science Team

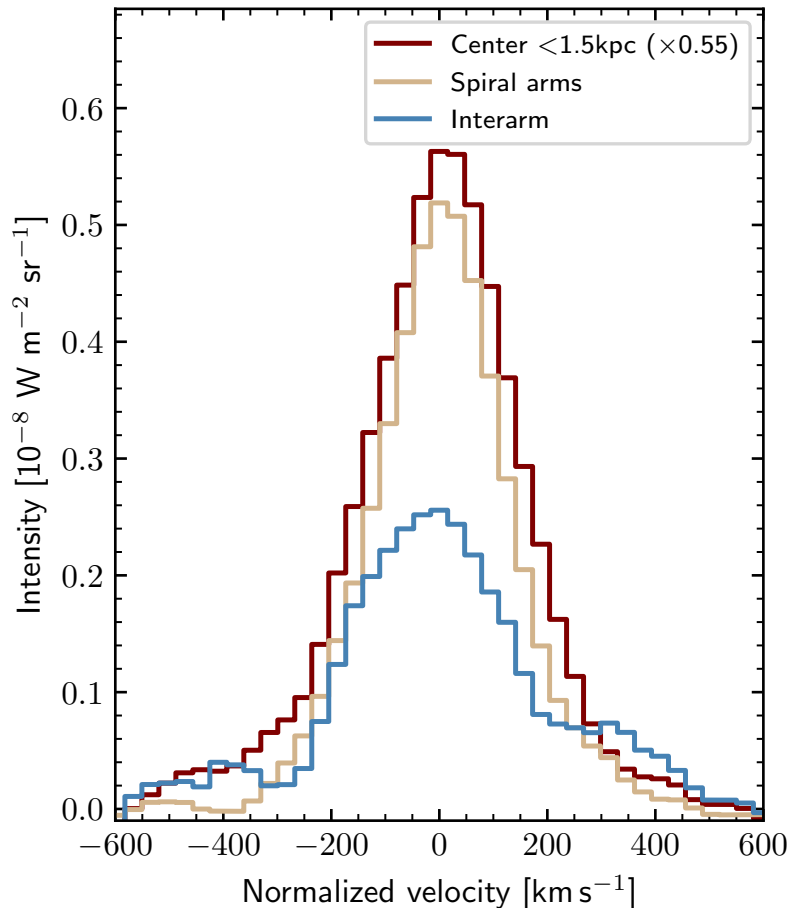
Full-Disk CII Mapping of NGC6946 with FIFI-LS



Spectral Stacking: Arms, Interarm, Center

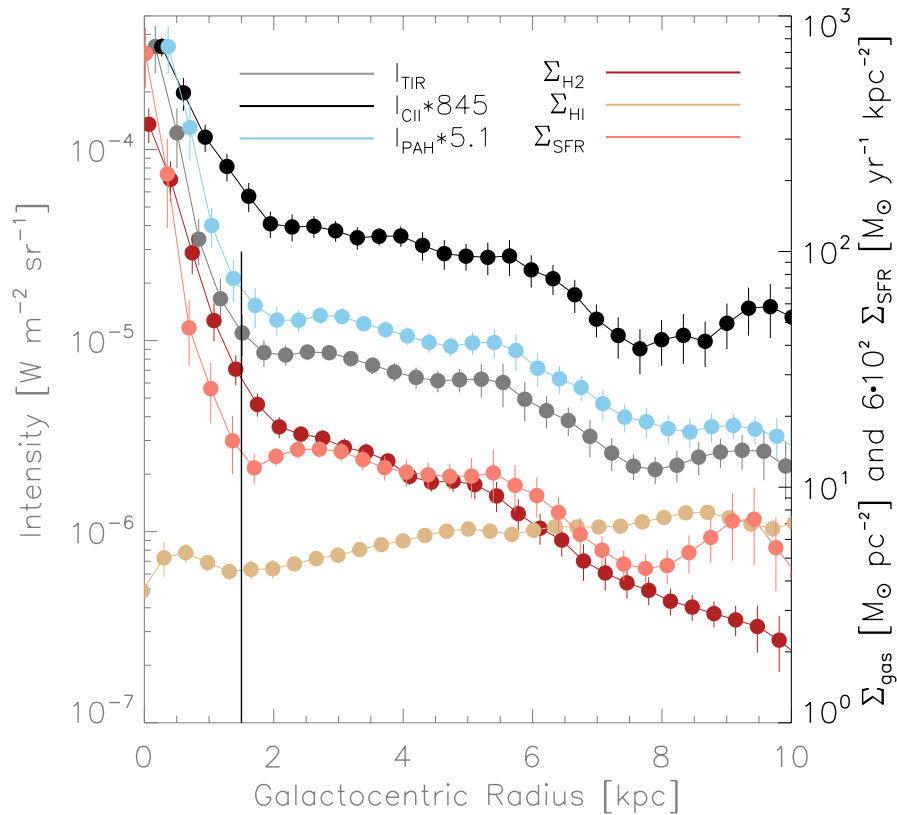


	Central 1.5 kpc	Spiral arms	Interarm
$[C II]/TIR [\cdot 10^{-3}]$	2.79 ± 0.04	5.65 ± 0.08	12.31 ± 0.47
$[C II]/CO [\cdot 10^2]$	1.45 ± 0.02	4.11 ± 0.06	5.29 ± 0.20
I_{70}/I_{100}	0.98 ± 0.05	0.80 ± 0.08	0.69 ± 0.23
$[C II]/I_{PAH} [\cdot 10^{-2}]$	1.26 ± 0.02	2.00 ± 0.03	4.02 ± 0.15



- Careful spectral stack to increase S/N - using CO as a prior - separating different dynamical regimes (arm, interarm, center).
- Line ratios (CII/TIR , CII/CO) in line with Herschel work (cf. Smith '17), in particular also central "CII deficits" ($CII/TIR \sim 0.1\%$).
- Integrated flux $\sim 73\%$ arm, 19% center, 8% interarm (cf. Contursi+ '02 for low fraction of interarm emission in NGC6946 from ISO, Pineda+ '18 for similar "disk" fraction of $\sim 75\%$ in M51).

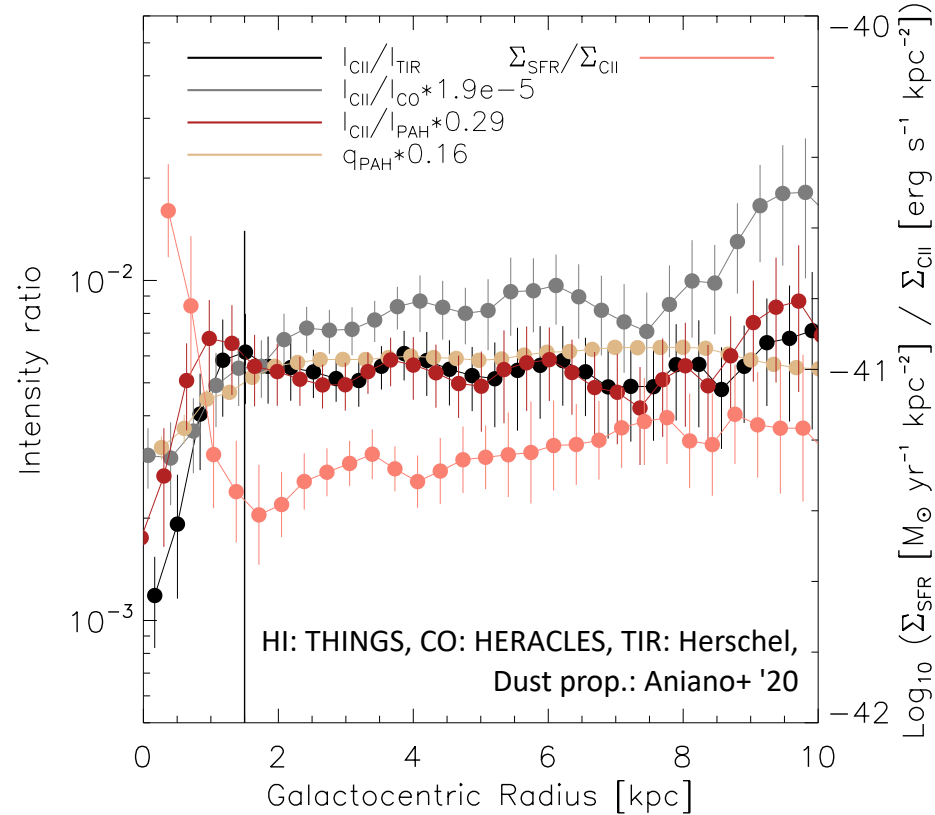
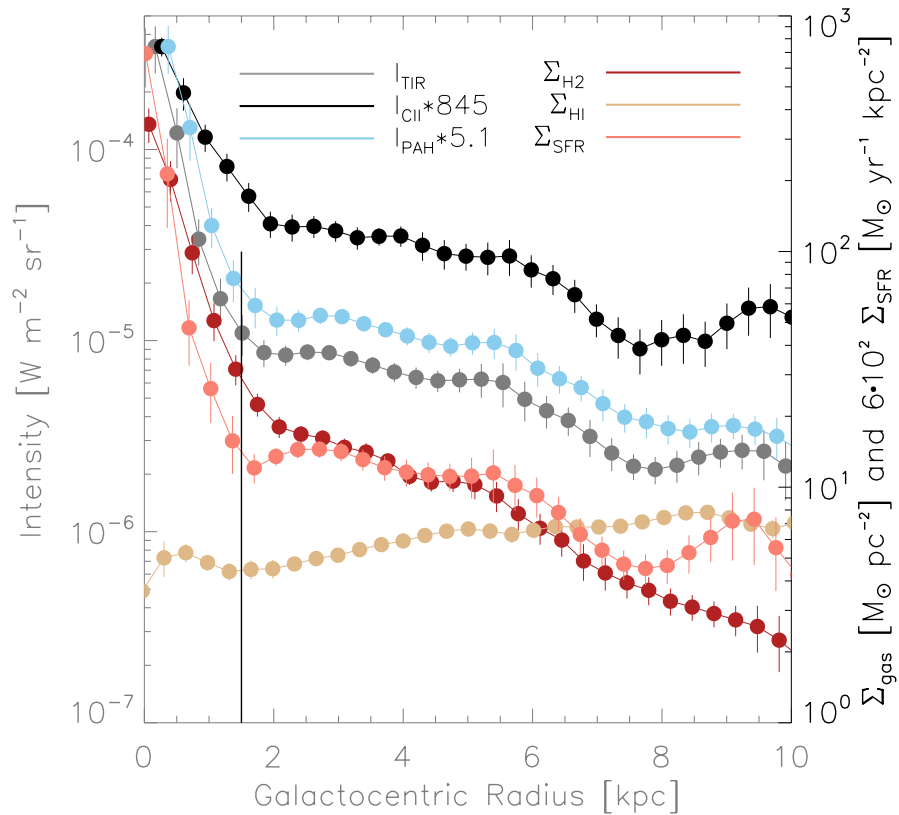
Radial Trends



HI: THINGS, CO: HERACLES, TIR: Herschel
Dust prop.: Aniano+ '20

- TIR, CII, PAH, H₂, SFR decline exponentially with scalelengths between ~ 3 -6 kpc (cf. de Blok '16 for several KINGFISH galaxies); H₂ is at the low, SFR and CII at the high end of scalelengths.
- The scatter (dominated by "astrophysical" variation by a factor of ~ 3 -10) in each ring rises from $\sim 20\%$ to $\sim 200\%$ with radius.

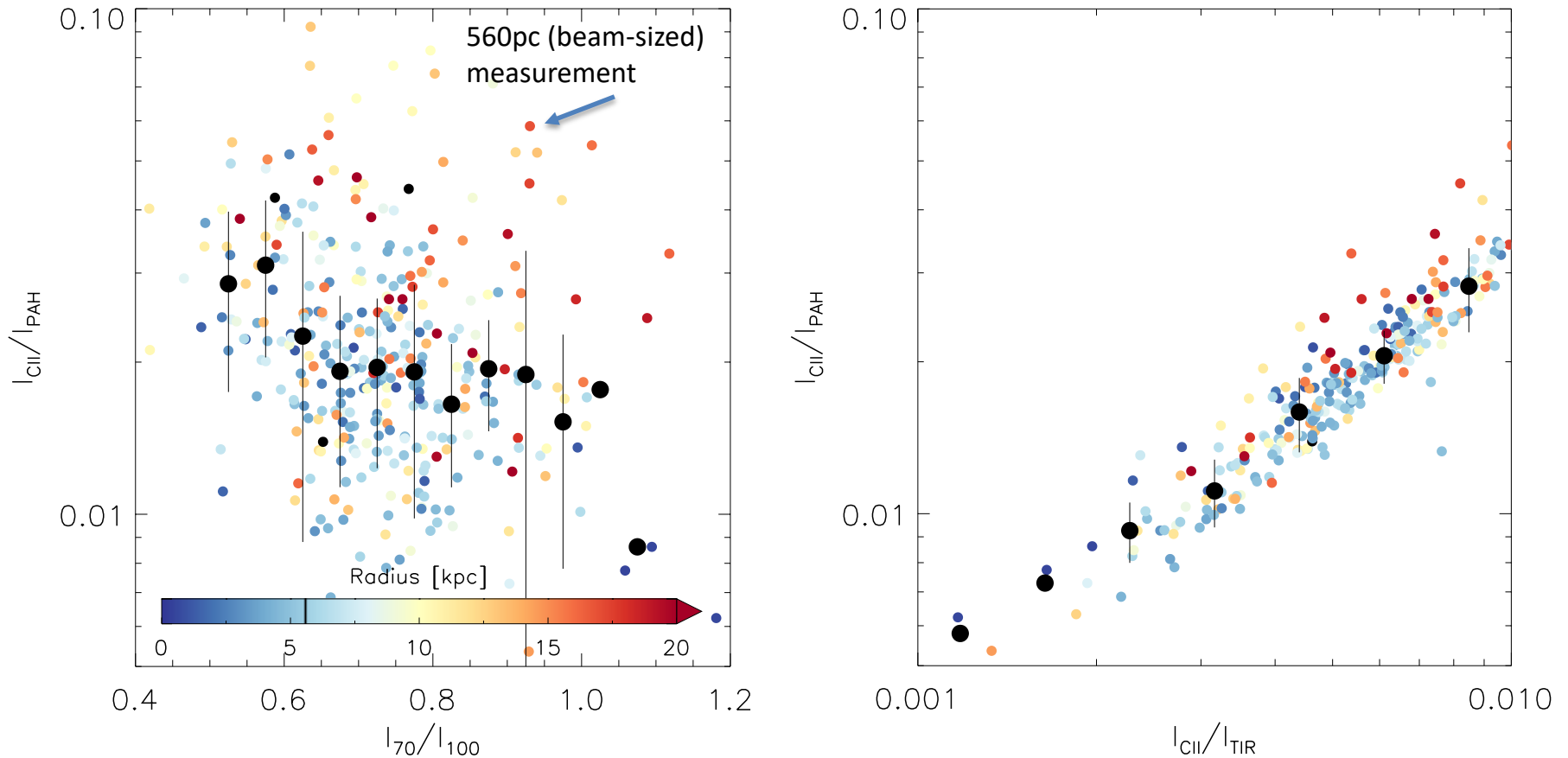
Radial Trends



HI: THINGS, CO: HERACLES, TIR: Herschel,
Dust prop.: Aniano+ '20

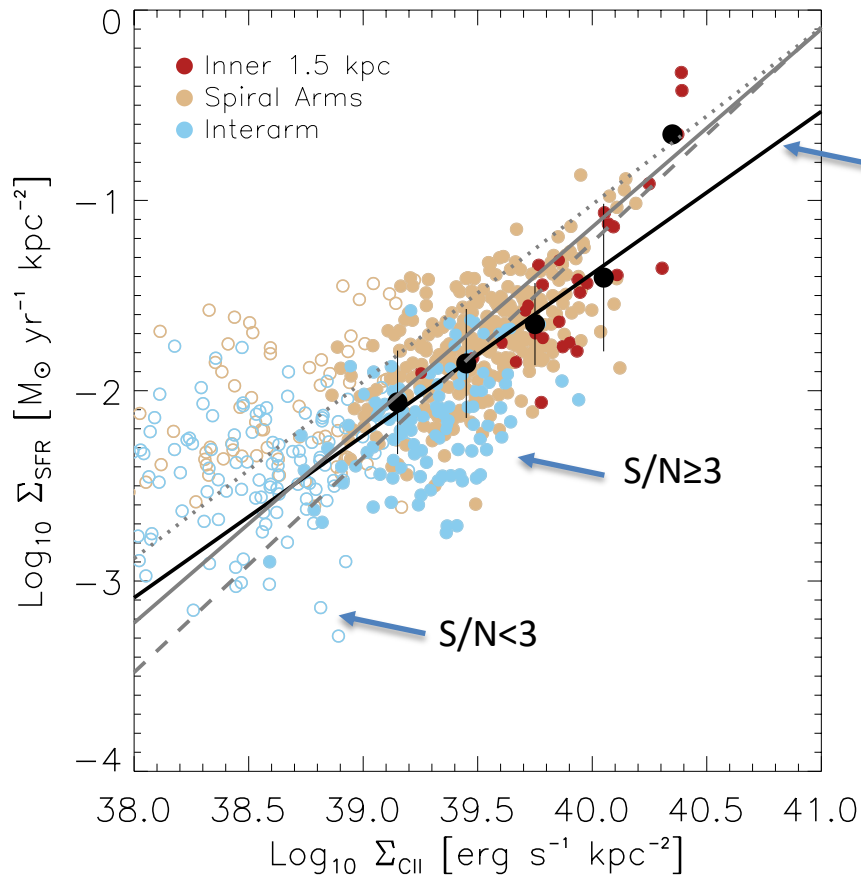
- Two distinct regimes: starburst inner ~ 1.5 kpc and "exponential disk" with distinct line ratio patterns.
- Specifically: Both CII/TIR (cf. Kramer+ '13, Kapala+ '15, Smith+ '17, etc.) and CII/CO rise in center and beyond ~ 8 kpc.

Neutral Gas Heating Efficiency



- CII "deficit" at high dust temperatures (cf. Croxall+ '12, Kapala+ '15). In the outer disk, CII/PAH (and CII/TIR) ratios are elevated.
- Ignoring contributions to CII from ionized gas and other cooling lines, PAHs may not be more closely linked to neutral gas heating than larger grains in this galaxy.

CII as a Star Formation Rate Tracer



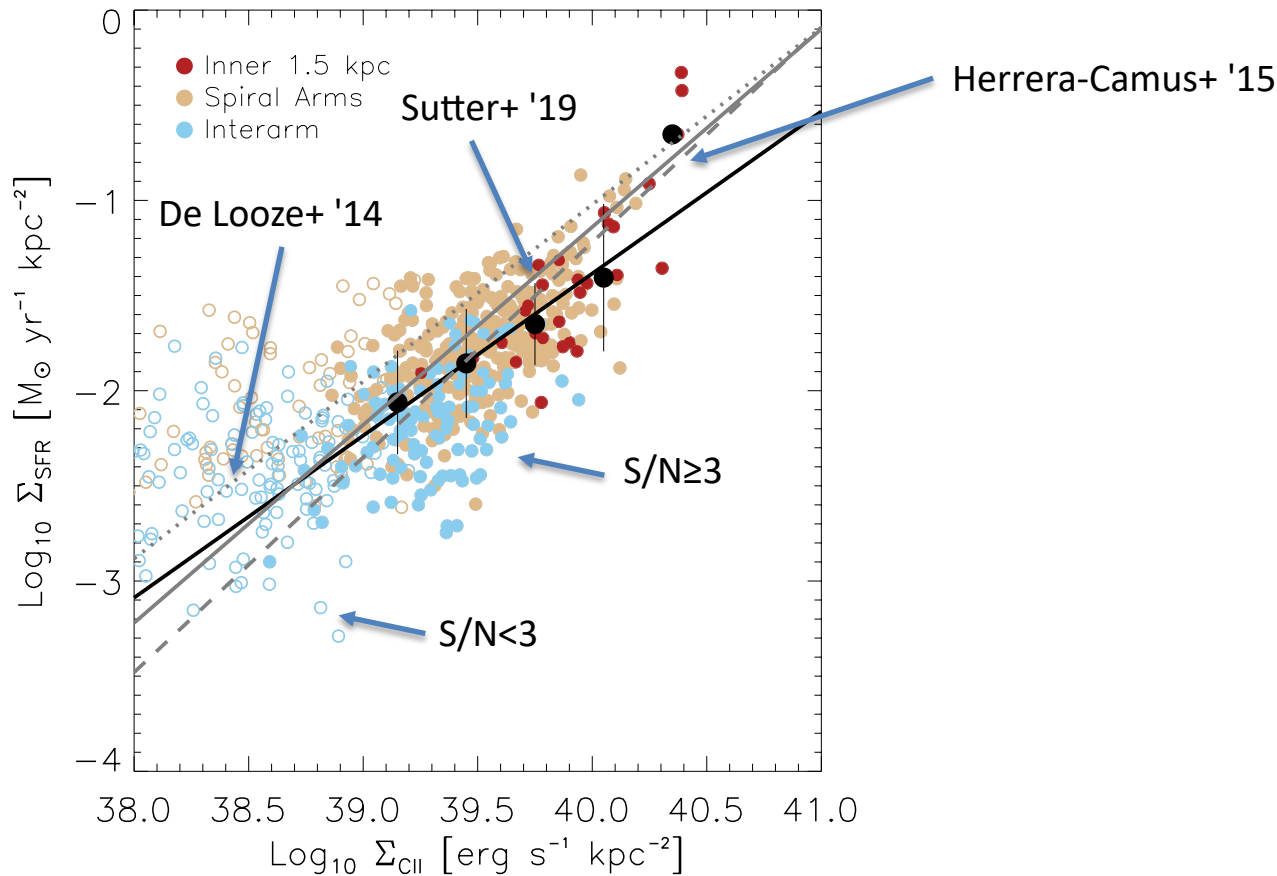
Simple linear regression to 560 pc-sized regions (only $S/N \geq 3$)

$S/N \geq 3$

$S/N < 3$

- Simple OLS y vs. x fit to 560pc-sized regions yields power law-slope of $N=0.85 \pm 0.05$ (though systematics matter!).

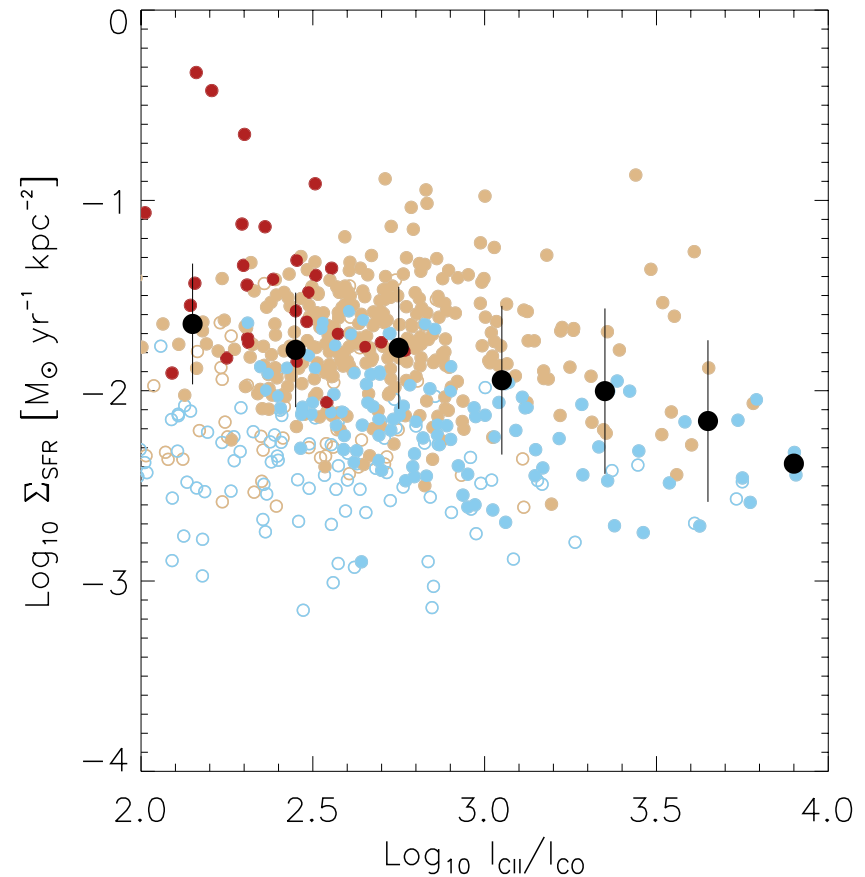
CII as a Star Formation Rate Tracer



- Simple OLS y vs. x fit to 560pc-sized regions yields power law-slope of $N=0.85 \pm 0.05$ (though systematics matter!).
- \sim Proportionality seems to be a good working model across the disks of local spiral galaxies (and dwarfs?), though mind the centers!

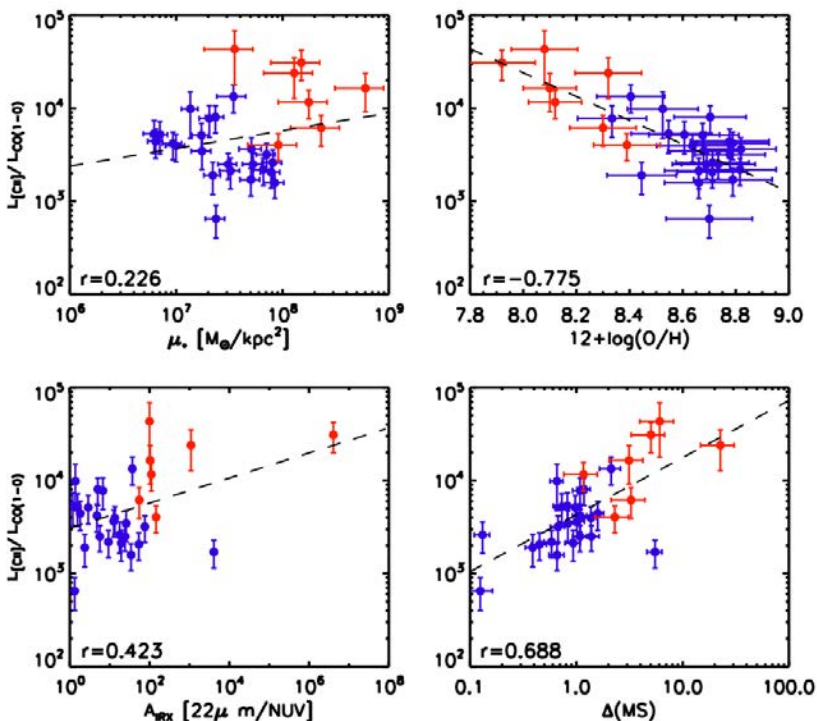
See also de Looze+ '14, Herrera-Camus+ '15, Pineda+ '14, '18, etc.

CII and "Diffuse" Molecular Gas



- Interarm regions cover broad range of CII/CO ratios, which specifically increase at large radii: radius (or correlated quantities) more closely linked to CII/CO than dynamical environment (also compare radial profiles).
- CII particularly important H_2 tracer where CO is faint.

CO-dark Gas Across NGC 6946 – Prescription from Accurso+ '17



Identify main sequence offset (ΔMS) and metallicity (z) as most closely correlated with CII/CO

Apply multi-phase radiative transfer and PDR/astrochemistry model to link CII/CO to α_{CO}

α_{CO} radial profile

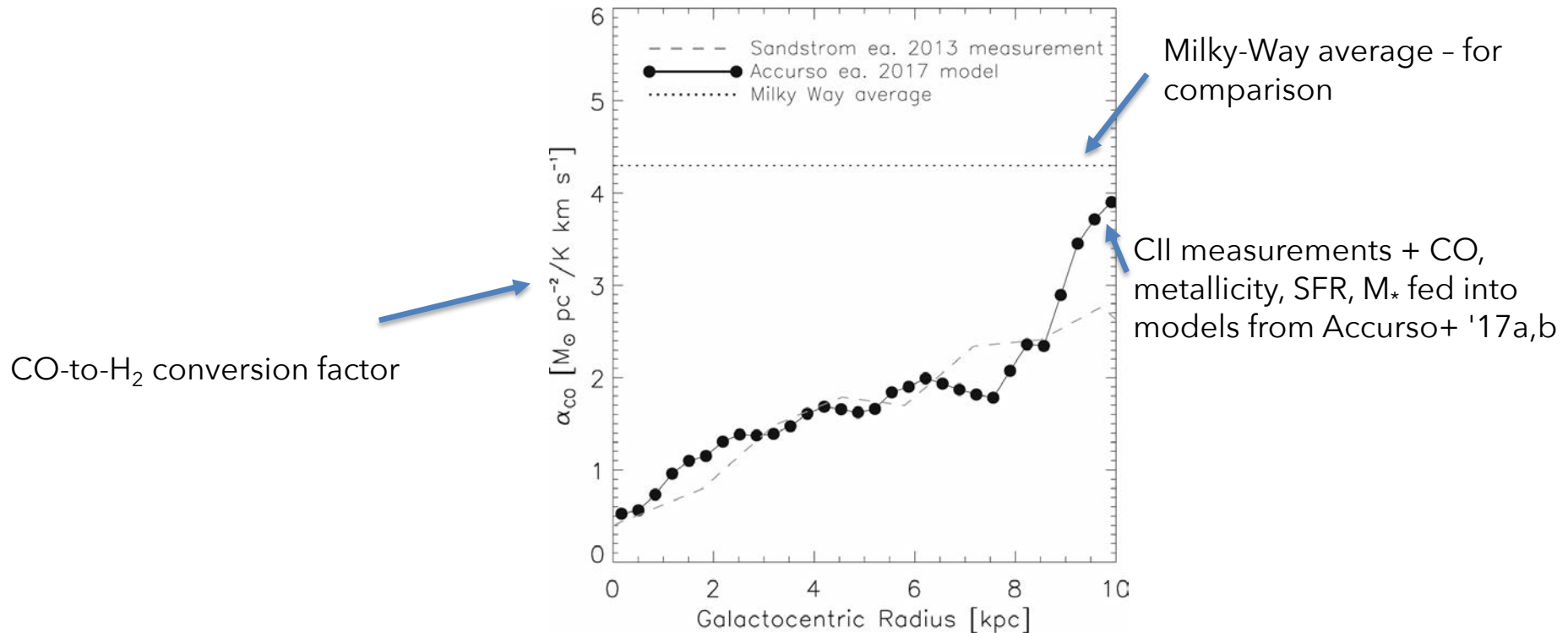
$\alpha_{CO}(L_{CII}/L_{CO}, z, \Delta MS)$

CII profile: this work
CO profile: HERACLES (IRAM 30m)

z profile/gradient (SINGS, Moustakas+ '10)

SFR profile (and main sequence SFR given z and M_*)

CO-dark Gas Across NGC 6946



- According to Accurso+ '17 model, α_{CO} is generally quite low compared to canonical Milky Way value (at face value implying a low CO-dark gas fraction) and increases gradually with radius (thus also metallicity).

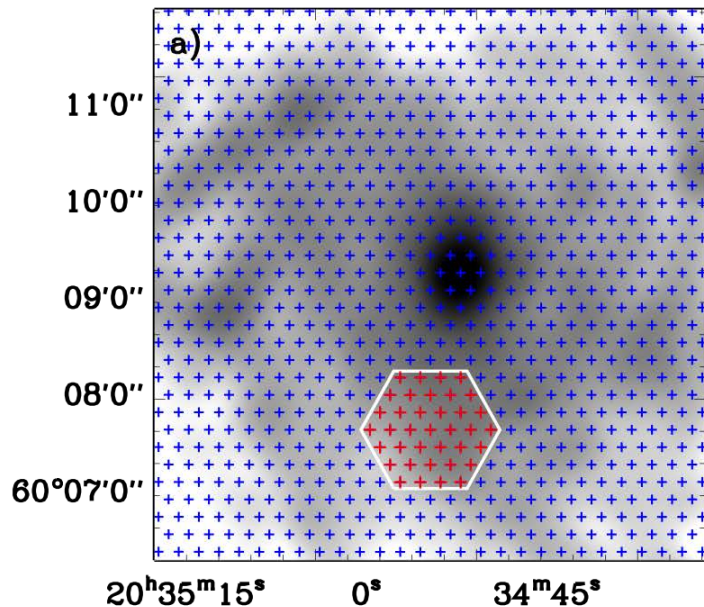
CO-dark Gas Across NGC 6946 – from Dust-to-Gas Ratios

Spitzer SINGS and Herschel KINGFISH VLA THINGS IRAM 30m HERACLES

$$\text{DGR} = \frac{\Sigma_{\text{D}}}{(\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}})}$$

DGR = dust-to-gas ratio *observable*

Assume DGR \sim constant on kpc scales.



Measure Σ_{D} , Σ_{HI} and I_{CO} at each point in a \sim kpc region.

CO-dark Gas Across NGC 6946 – from Dust-to-Gas Ratios

Spitzer SINGS and Herschel KINGFISH

VLA THINGS

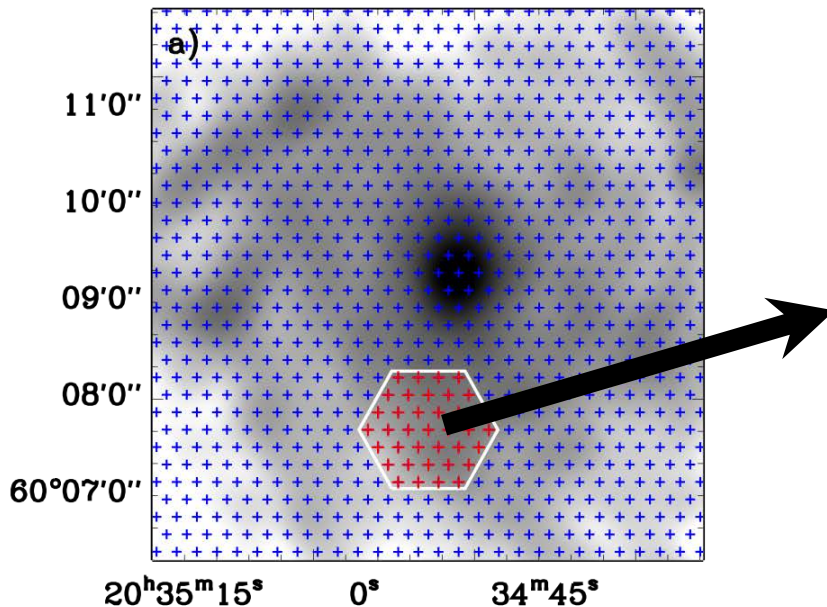
IRAM 30m HERACLES

$$\text{DGR} = \frac{\Sigma_D}{(\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}})}$$

DGR = dust-to-gas ratio

observable

Assume DGR \sim constant on kpc scales.



$$\text{DGR}_0 = \frac{\Sigma_{D,0}}{(\Sigma_{\text{HI},0} + \alpha_{\text{CO}} I_{\text{CO},0})}$$

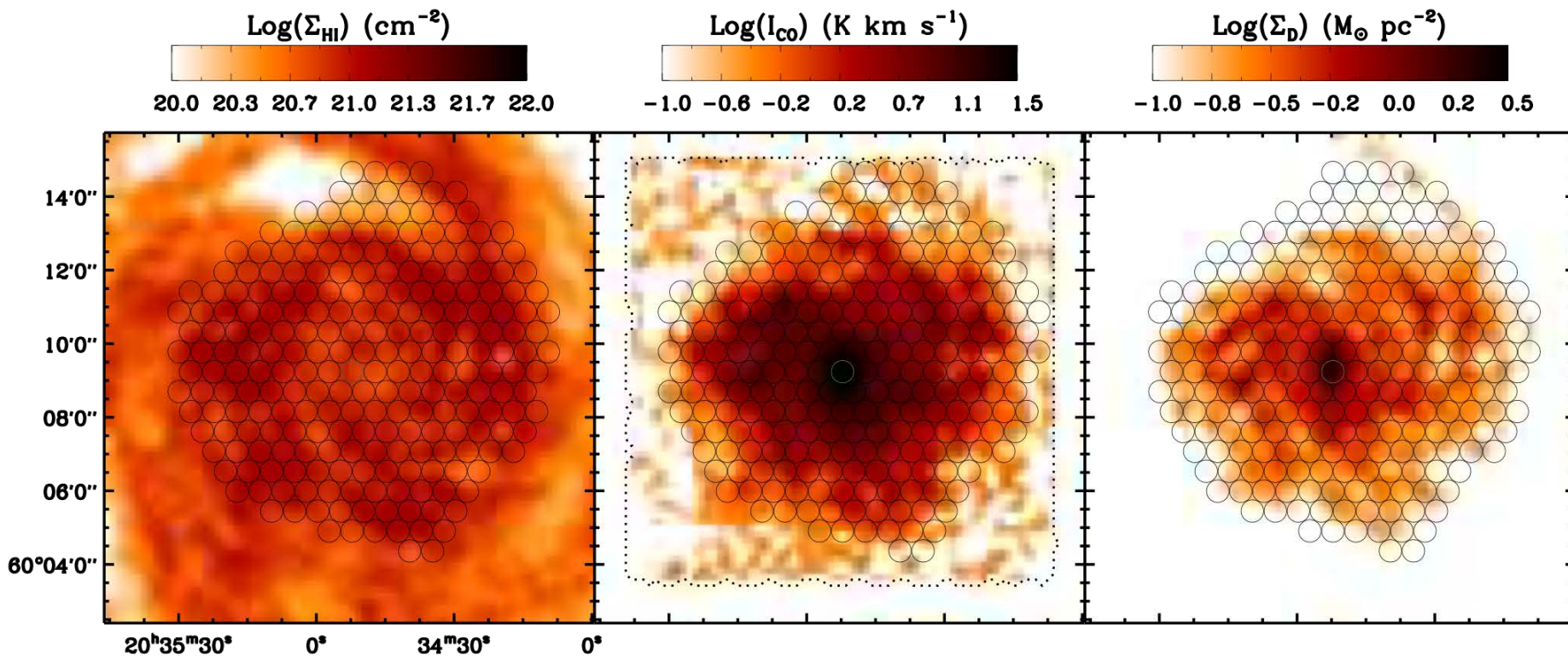
$$\text{DGR}_1 = \frac{\Sigma_{D,1}}{(\Sigma_{\text{HI},1} + \alpha_{\text{CO}} I_{\text{CO},1})}$$

$$\text{DGR}_2 = \frac{\Sigma_{D,2}}{(\Sigma_{\text{HI},2} + \alpha_{\text{CO}} I_{\text{CO},2})}$$

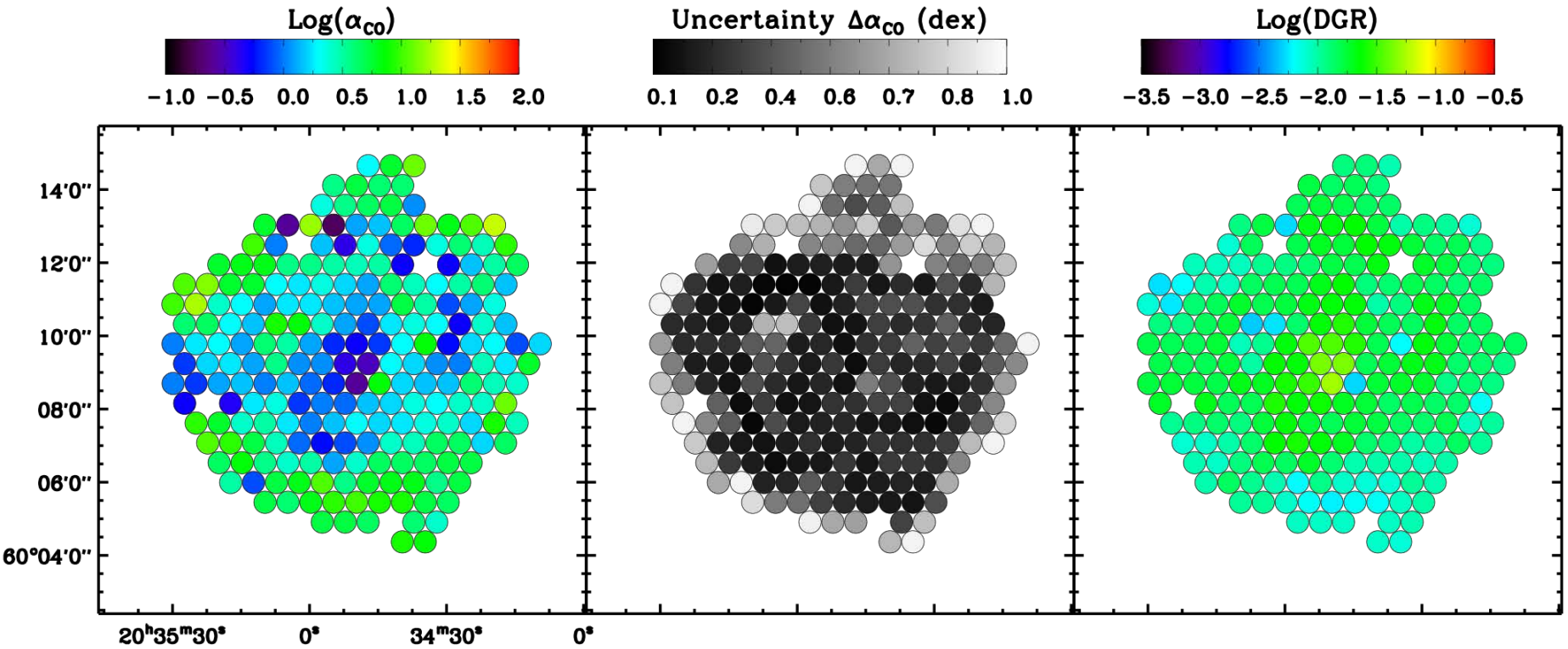
...

$$\text{DGR}_N = \frac{\Sigma_{D,N}}{(\Sigma_{\text{HI},N} + \alpha_{\text{CO}} I_{\text{CO},N})}$$

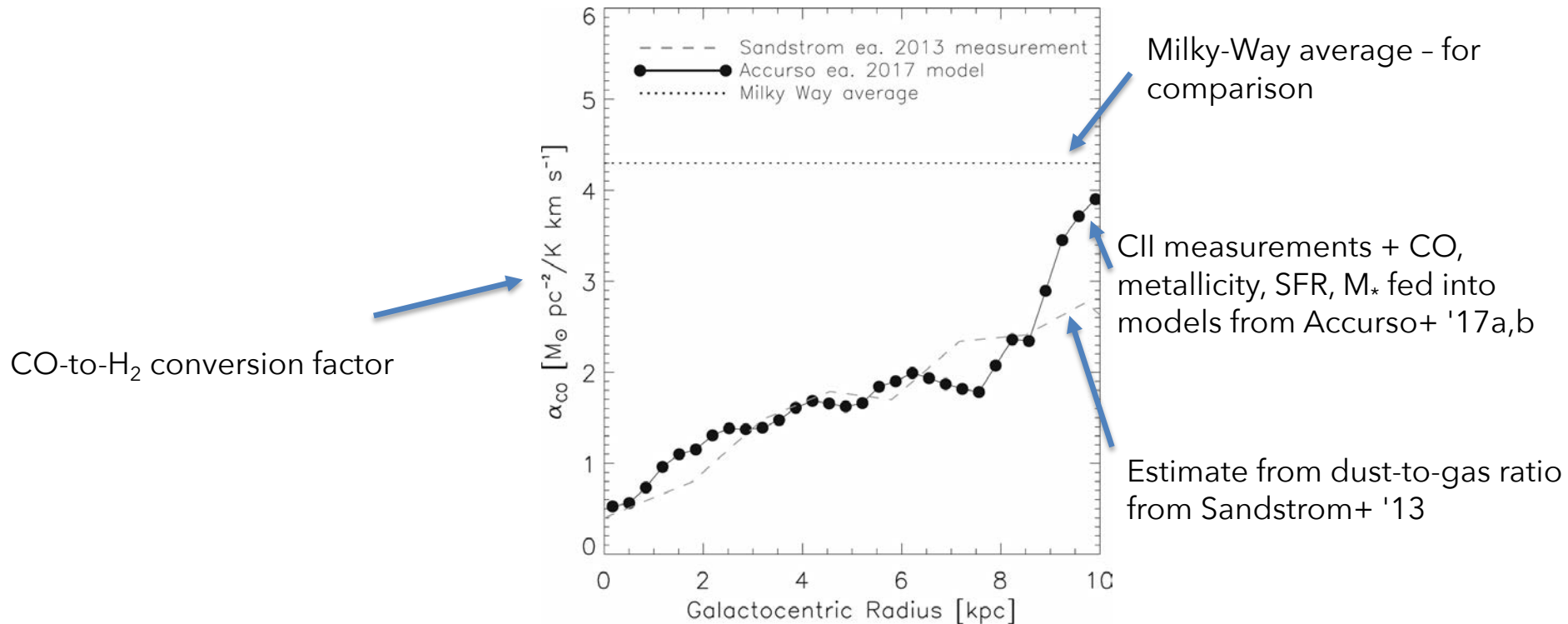
CO-dark Gas Across NGC 6946 – from Dust-to-Gas Ratios



CO-dark Gas Across NGC 6946 – from Dust-to-Gas Ratios



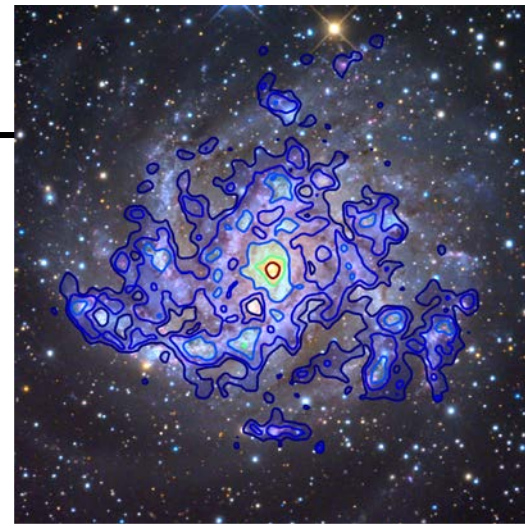
CO-dark Gas Across NGC 6946



- Excellent agreement to (independent) dust-to-ratio estimates from Sandstrom+ '13 (and also Amorín+ '16, based on empirical SFR/H₂-metallicity calibration for galaxy average).
- Possible drivers for low (central) values: CO excitation, high gas-phase carbon abundance and dynamical broadening reducing optical depth

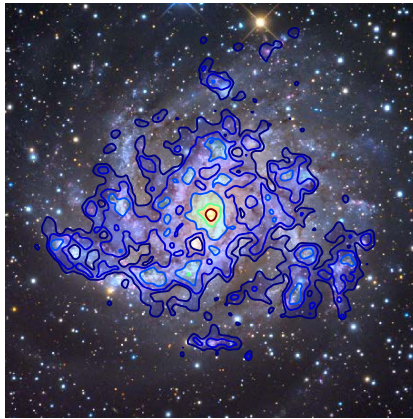
Summary

- SOFIA/FIFI-LS (and upGREAT) well suited for efficient, wide-field maps of nearby galaxies to get statistics across diverse galactic environments. Local Galaxies are a sweetspot, combining diverse environments (within and among galaxies) and are close enough to resolve scales of a few 100pc.

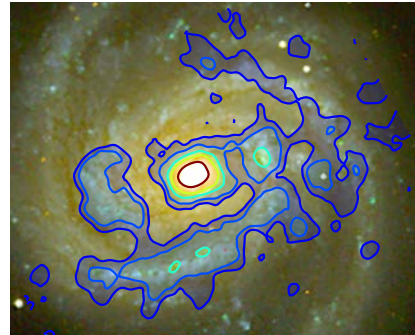


- NGC6946 case study shows significant and systematic variation of key line ratios like CII/TIR, CII/CO or SFR/TIR in particular in centers (CII-deficit) and at large radii, confirming prior results.
- SFR-CII scaling relation with power-law slope of \sim unity matches prior work (though centers deviate!) - methodology matters!
- Using the SOFIA CII observations in combination with published models, the CO-dark molecular gas fraction is much lower than in the Milky Way, but rises across the disk. This is consistent among different, independent models.
- More full-galaxy CII maps to be expected from upGREAT and FIFI-LS ...

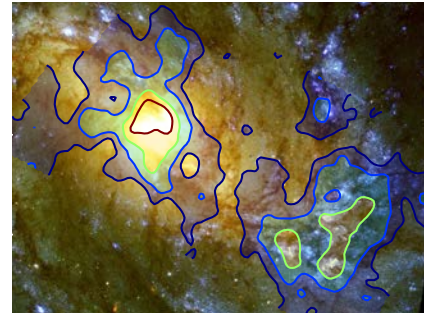
Outlook



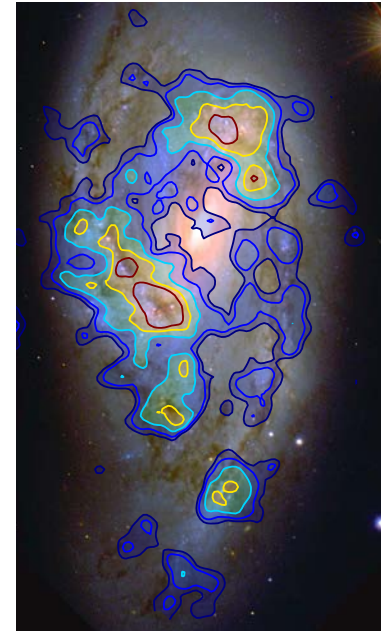
NGC6946



NGC4321



M83 - partial



NGC3627

FIFI-LS CII mapping of nearby spiral galaxies
(together with A. Krabbe & the FIFI-LS science team)

Outlook

Work in progress!

