[CII] and [NII] in the nucleus of IC 342

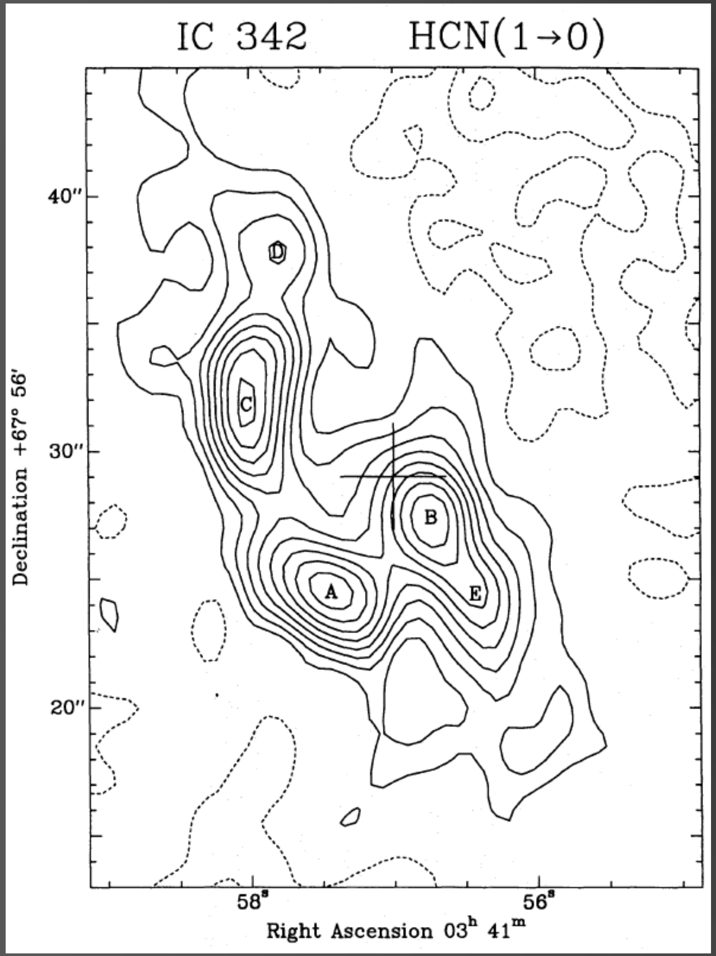
M. Röllig
Universität zu Köln, Germany

Introduction

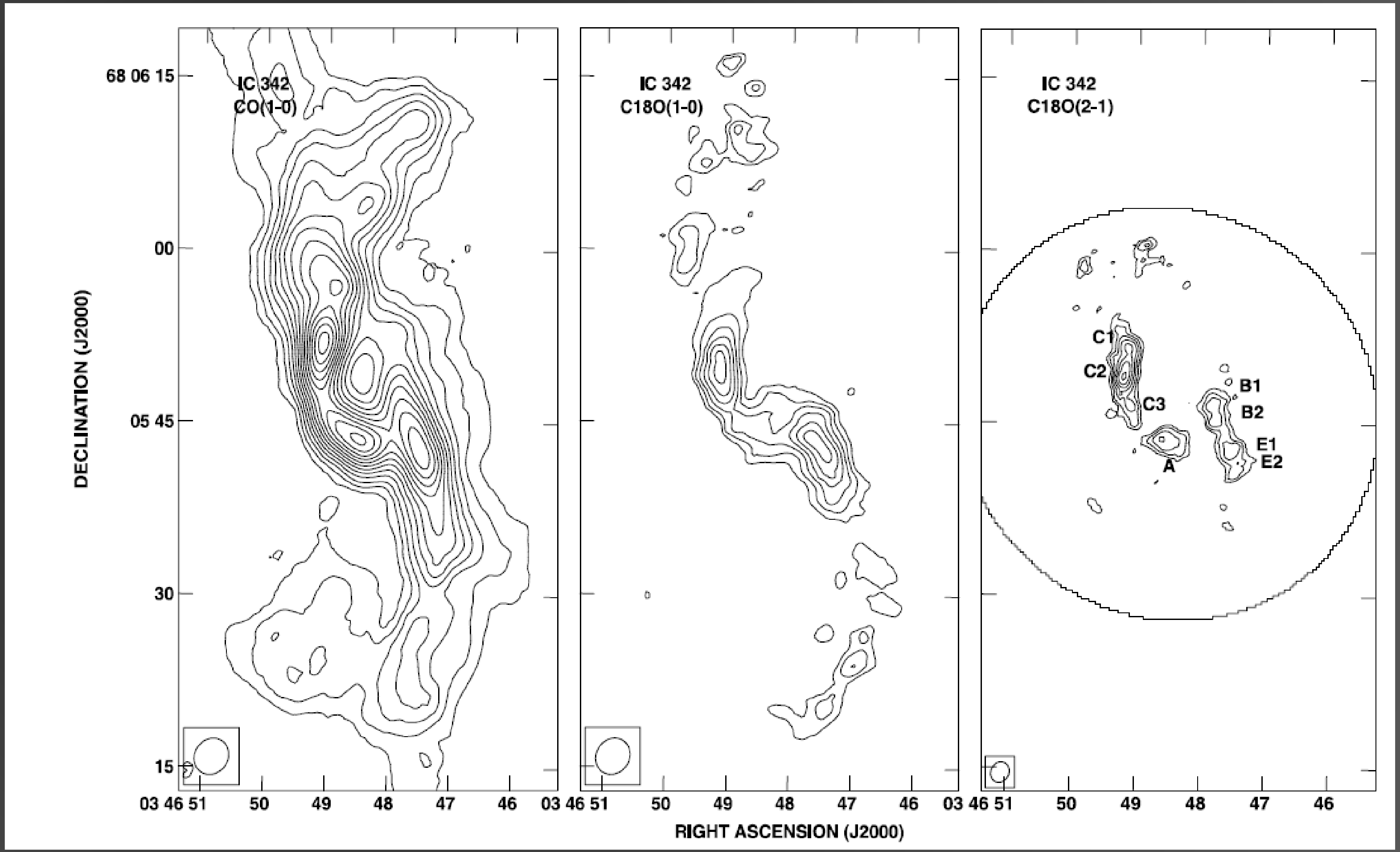
NASA/JPL-Caltech/UCLA -

- Barred spiral obscured by the plane of the MW
- D=3.3 Mpc
- Starburst activity in the center
- Sometimes considered a „close relative“ to the MW

The Nucleus of IC 342

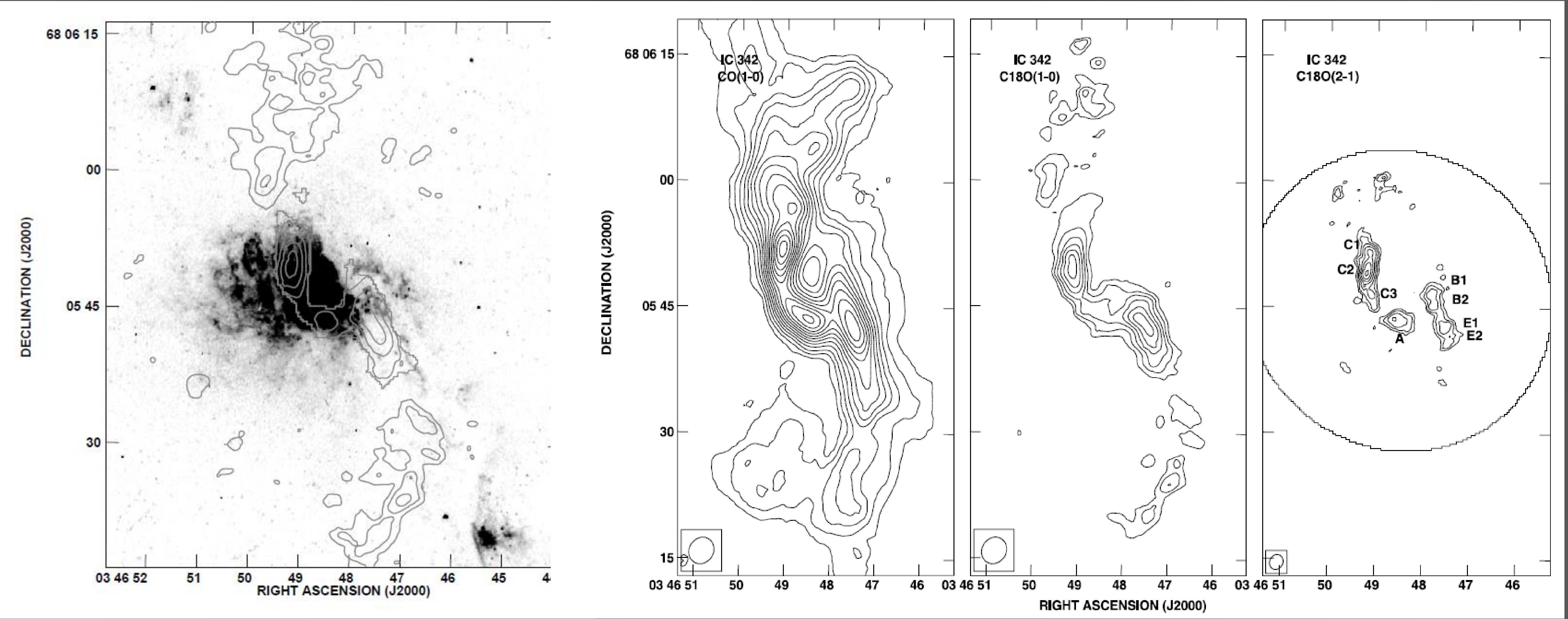


Downes et al. 1992



Meier & Turner 2001

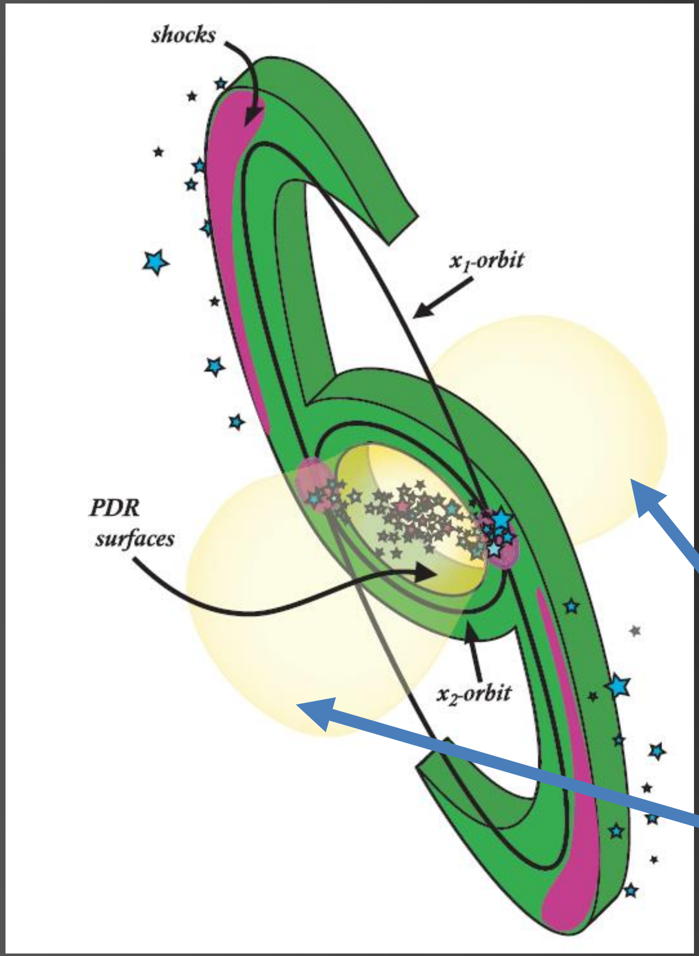
The Nucleus of IC 342



N(H_2) on HST Hα

Meier & Turner 2001

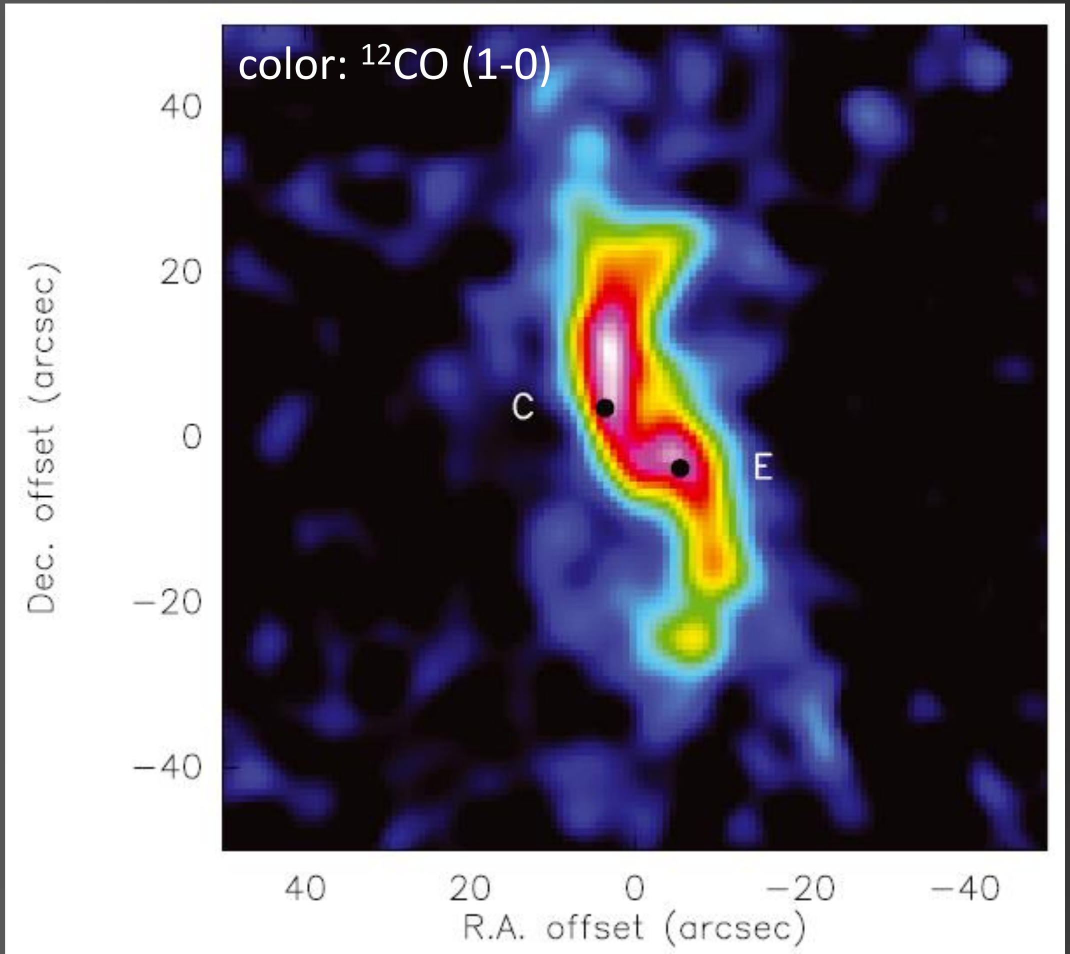
IC 342 – Geometry of the inner 300pc

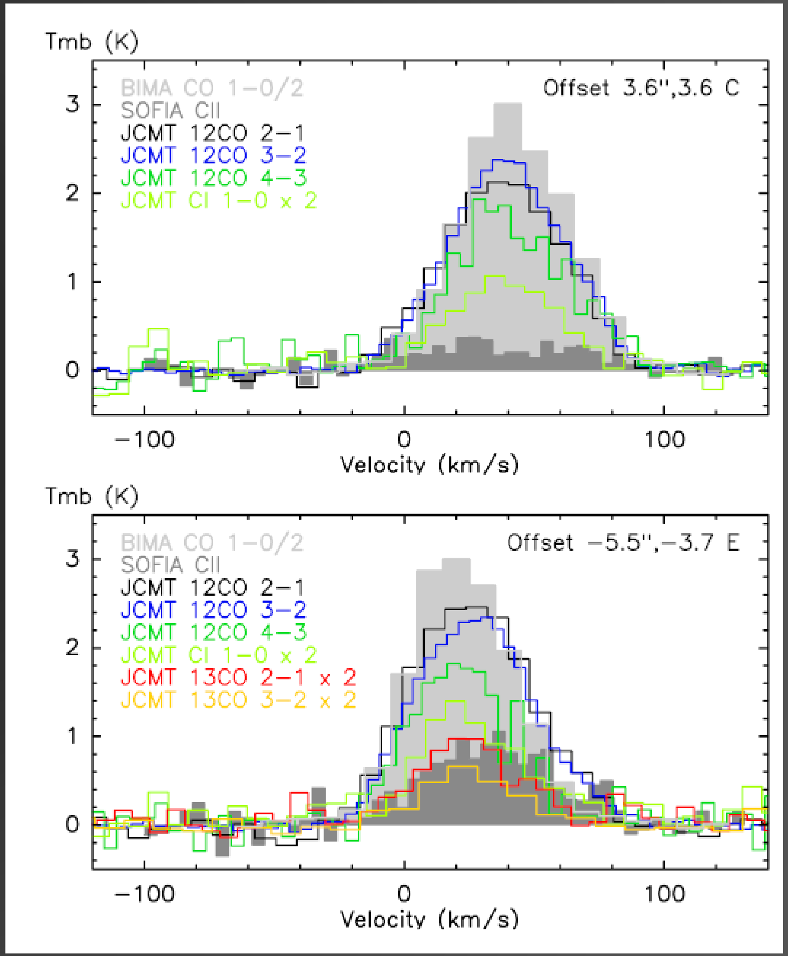


Meier & Turner 2005

- Bar-potential leads to mini-spiral configuration in the nucleus
- The spiral arms end at an inner molecular ring
- The center of the ring is dominated by an evolved (60 Myr) massive star cluster
- The inner rim of the ring is illuminated by FUV → PDR emission
- Expanding bubbles of HII gas

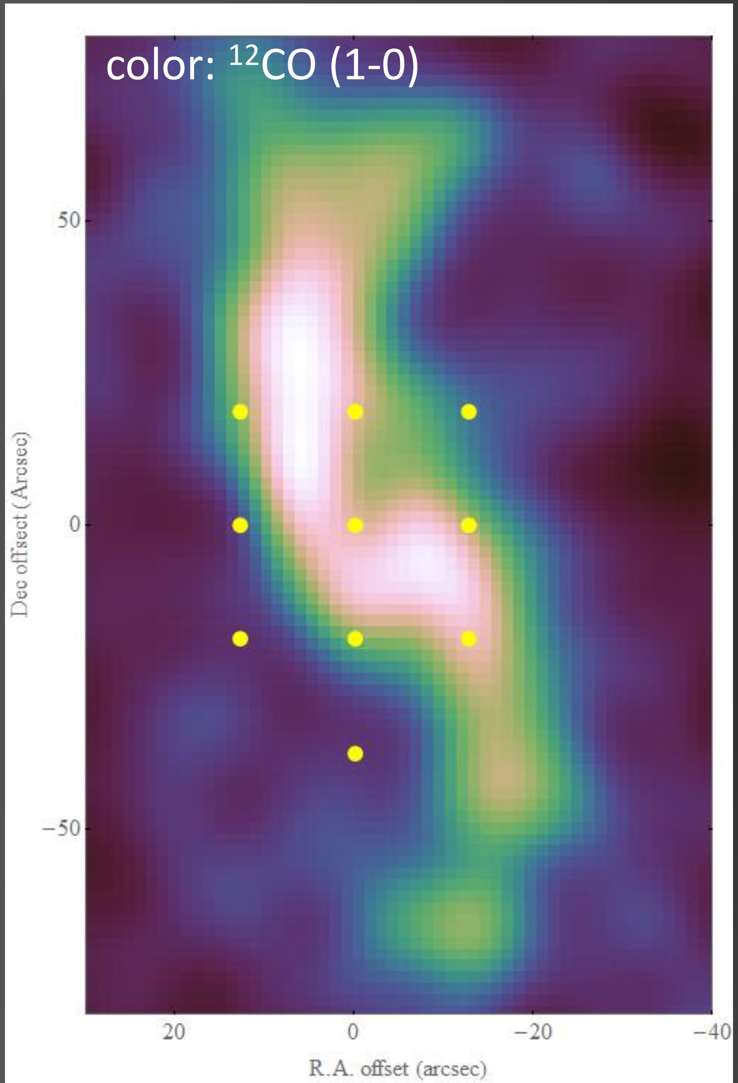
First SOFIA observations 2011 (SS1)





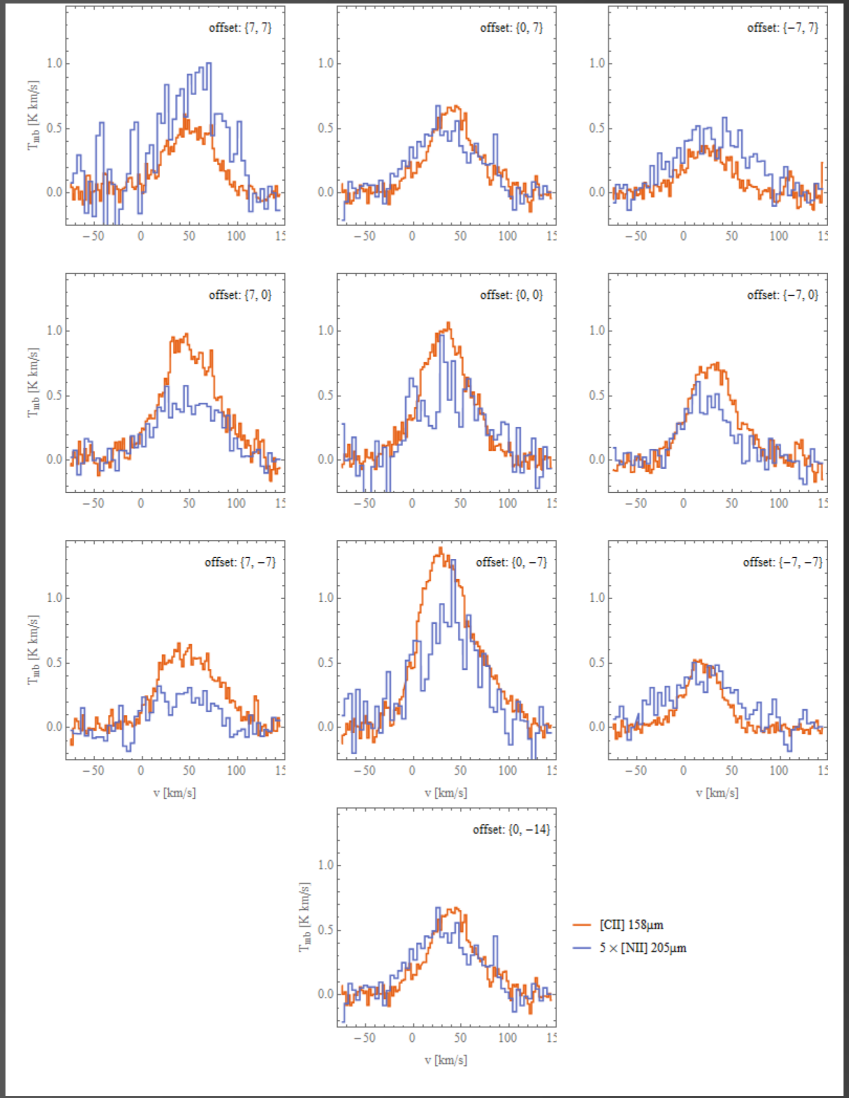
Röllig et al. 2012

SOFIA/GREAT observations 2013/14



- 10 positions in dual-beam switch mode observed in 3 flights
- L1/L2 GREAT configuration
  L1: [NII] $^3P_1$-$^3P_0$ 205 μm
  L2: [CII] $^3P_{3/2}$-$^3P_{1/2}$ 158μm
- t_{ON}=2.5min – 7.5min
- T_{sys}=2000-5500 K
- 8192 channel FFTS with 1.5 GHz bandwidth and 212 kHz spectral resolution

SOFIA/GREAT observations 2013/14

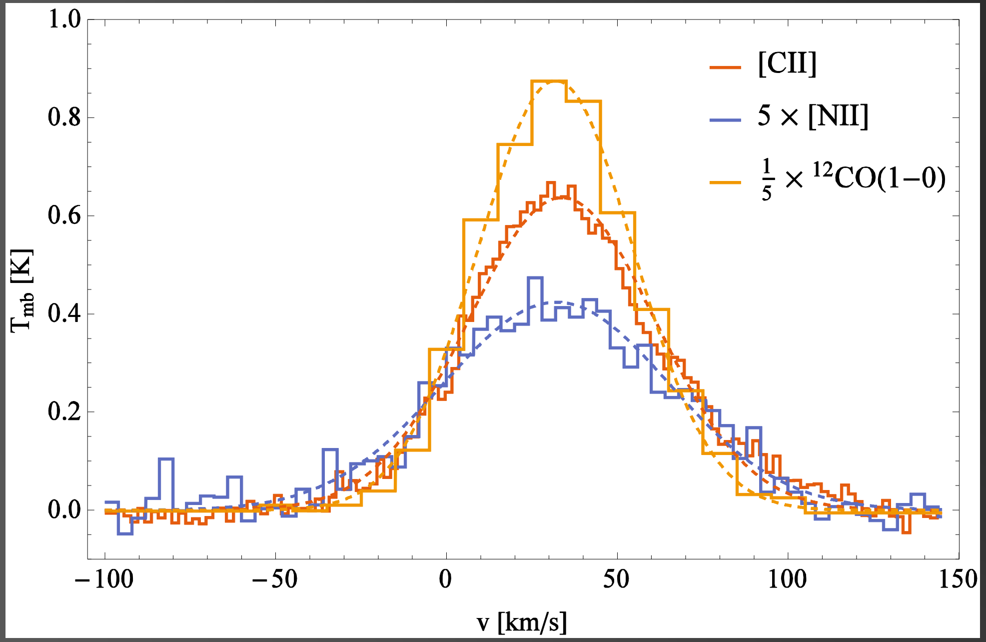


- 10 positions (spacing 7'') in dual-beam switch mode observed during 3 flights
- L1/L2 GREAT configuration
  - L1: [NII] $^3P_1$-$^3P_0$ 205µm
  - L2: [CII] $^3P_{3/2}$-$^3P_{1/2}$ 158µm
- t_{ON}=2.5min – 7.5min
- T_{sys}=2000-5500 K
- 8192 channel FFTS with 1.5 GHz bandwidth and 212 kHz spectral resolution
- $RMS_{[NII]}$<100mK
  $RMS_{[CII]}$<60mK

red: [CII], blue: [NII] ×5

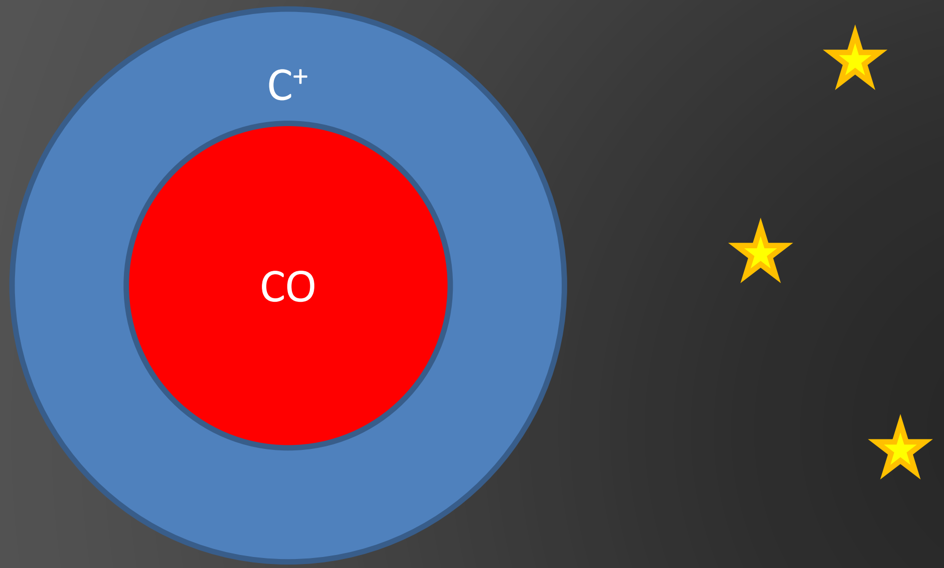
SOFIA/GREAT observations 2013/14

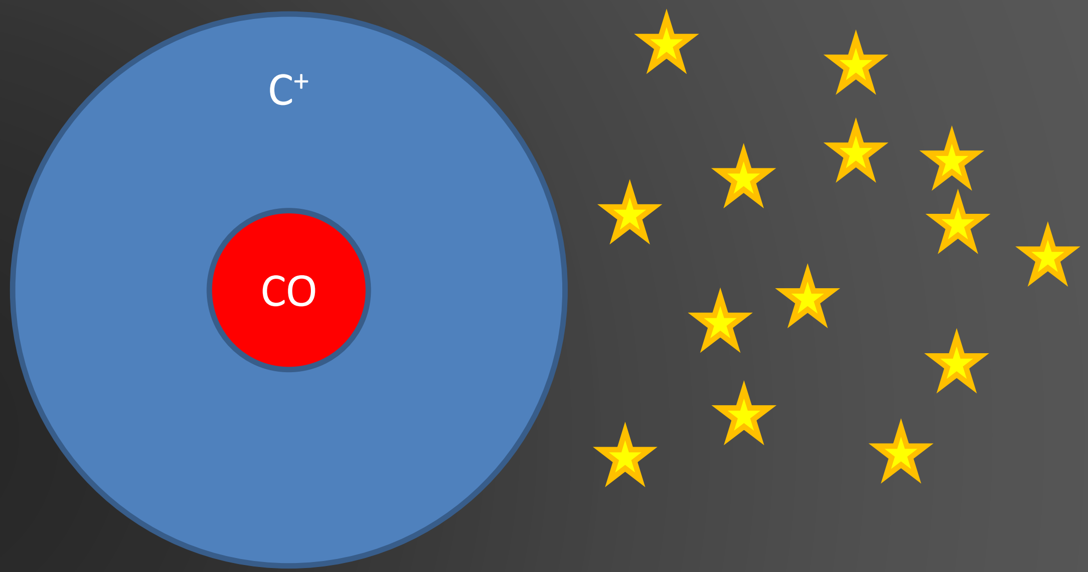
average spectrum over central 3x3



- 10 positions in dual-beam switch mode observed during 3 flights
- L1/L2 GREAT configuration
  L1: [NII] $^3P_1$-$^3P_0$ 205 µm
  L2: [CII] $^3P_{3/2}$-$^3P_{1/2}$ 158µm
- t_{ON}=2.5min – 7.5min
- T_{sys}=2000-5500 K
- 8192 channel FFTS with 1.5 GHz bandwidth and 212 kHz spectral resolution
- $RMS_{[NII]}$<100mK
  $RMS_{[CII]}$<60mK

[CII]/CO as star formation tracer

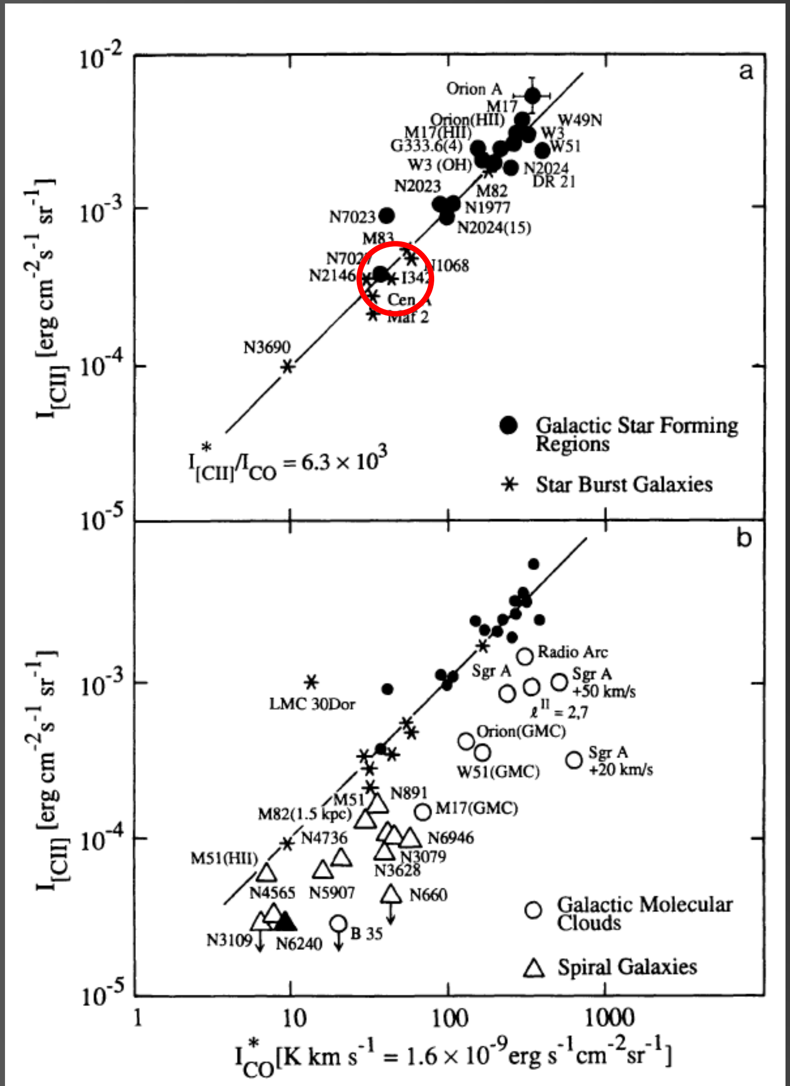




- The intensity ratio [CII]/^{12}CO(1-0) is often used as tracer of star formation/PDR/star burst activity
- [CII] emission scales with FUV illumination
- Stronger FUV illumination from massive stars leads to stronger [CII]

- CO forms in the cool, shielded parts of the ISM
- Stronger FUV illumination leads to a decrease in N(CO) together with a reduced area filling factor

[CII]/CO as star formation tracer



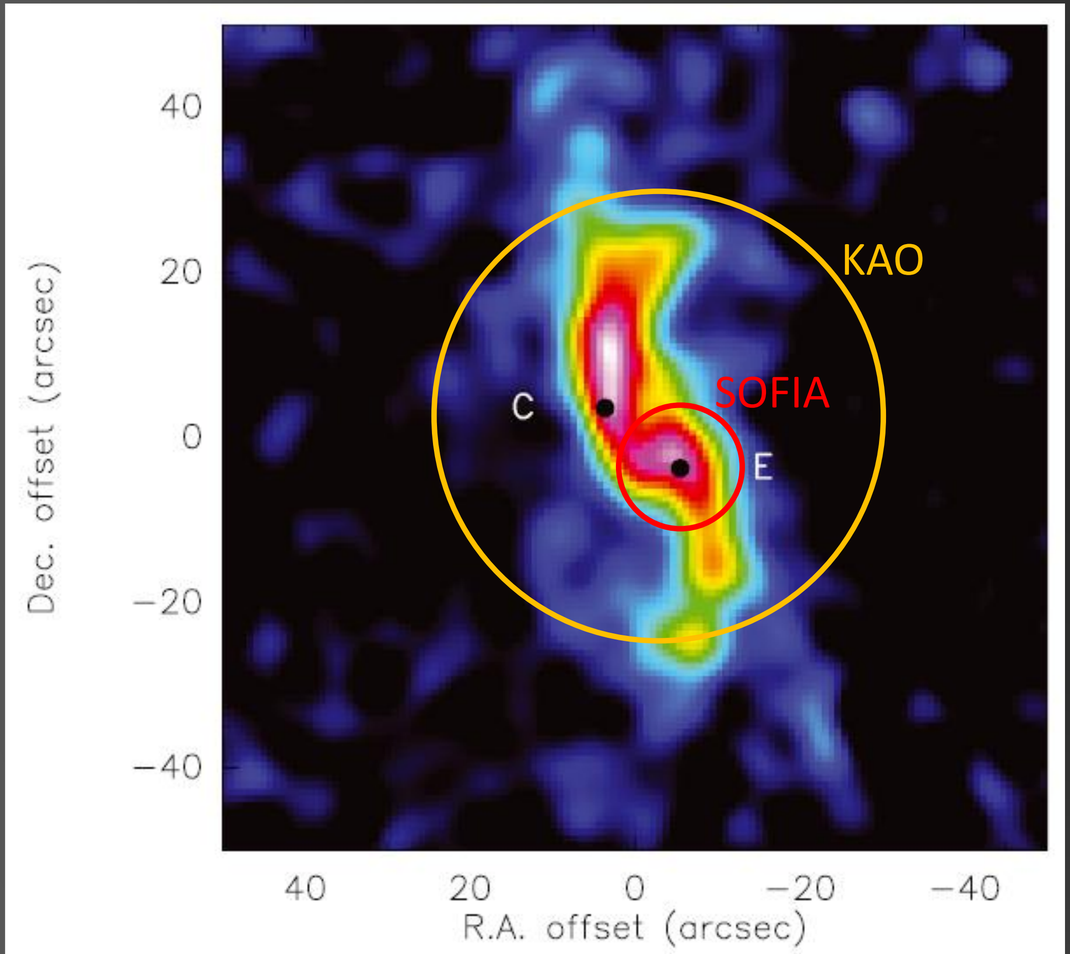
Stacey et al. 1991

- $I_{[CII]}/I_{CO}$=4000-6000 is indicative of strong PDR activity/star bursts
- I_{CO}=37.7±1.8 K km/s @ 65" beam (NRAO, Rickard & Blitz 1985)
- $I_{[CII]}=3\times10^{-4}$ erg/s/cm²/sr @ 55" beam (KAO, Crawford et al. 1985)

Compare with higher resolution data

- I_{CO}=302 K km/s @ 15" (BIMA, smoothed)
  $I_{[CII]}=4.1\times10^{-4}$ erg/s/cm²/sr @ 15" (SOFIA)

KAO compared to SOFIA

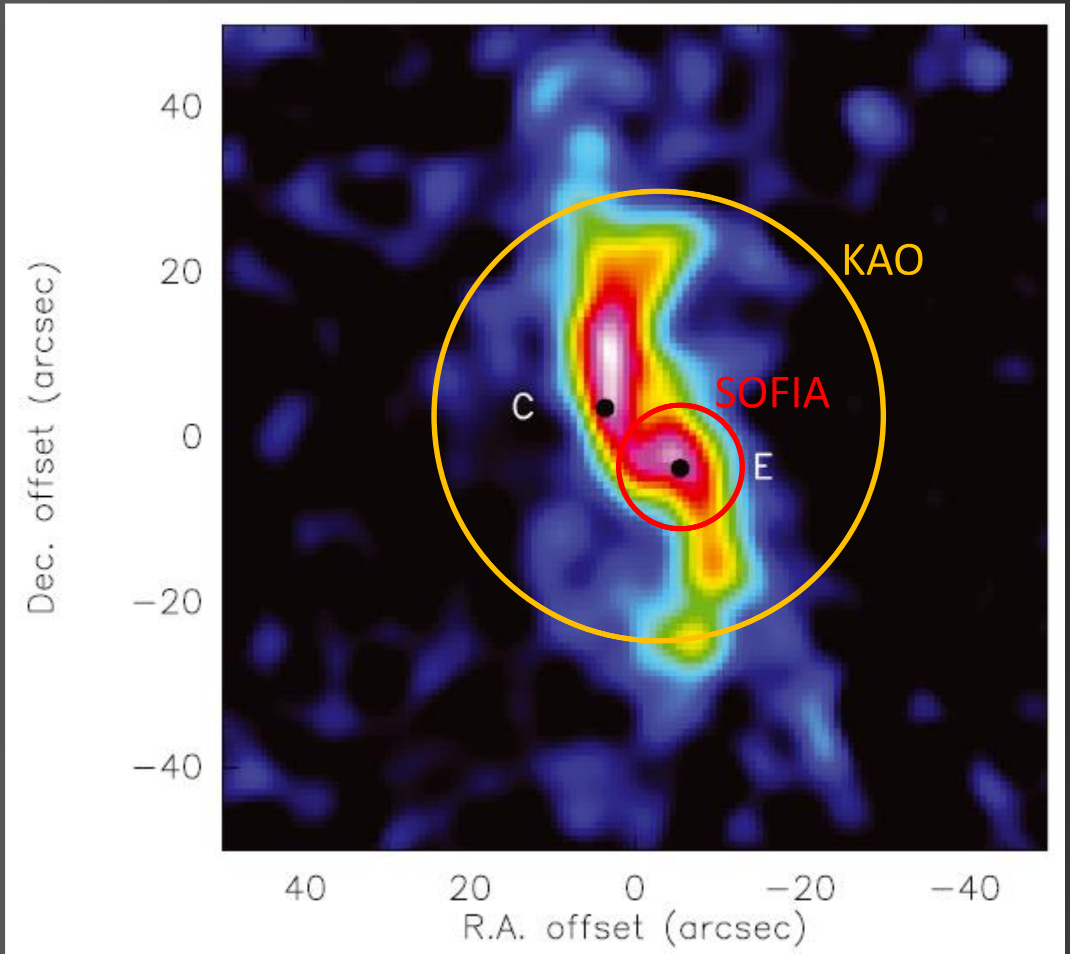


Stacey et al. 1991: [CII]/CO=5000

	GMC C	GMC E
[C II]/^{12}CO(1–0)	482	4236/692
[C II]/^{12}CO(2-1)	142	1223/150
[C I]/^{12}CO(1–0)	6.5	–/9.4
[C I]/^{12}CO(2–1)	1.9	–/2.4
^{12}CO(4–3)/^{12}CO(1–0)	20.7	21.1(–)
$N_{[CII]}/[10^{17}\mathrm{cm}^{-2}]^a$	1.4	0.9/1.6
PDR model results		
$\langle n \rangle$ [10^3 cm^{-3}]	5.0	10/2.0
$M_{\rm tot}$ [10^6 $M_\odot$]	20	2.0/15
χ [Draine]	7	300/5

As always: higher angular resolution leads to a more complex picture.

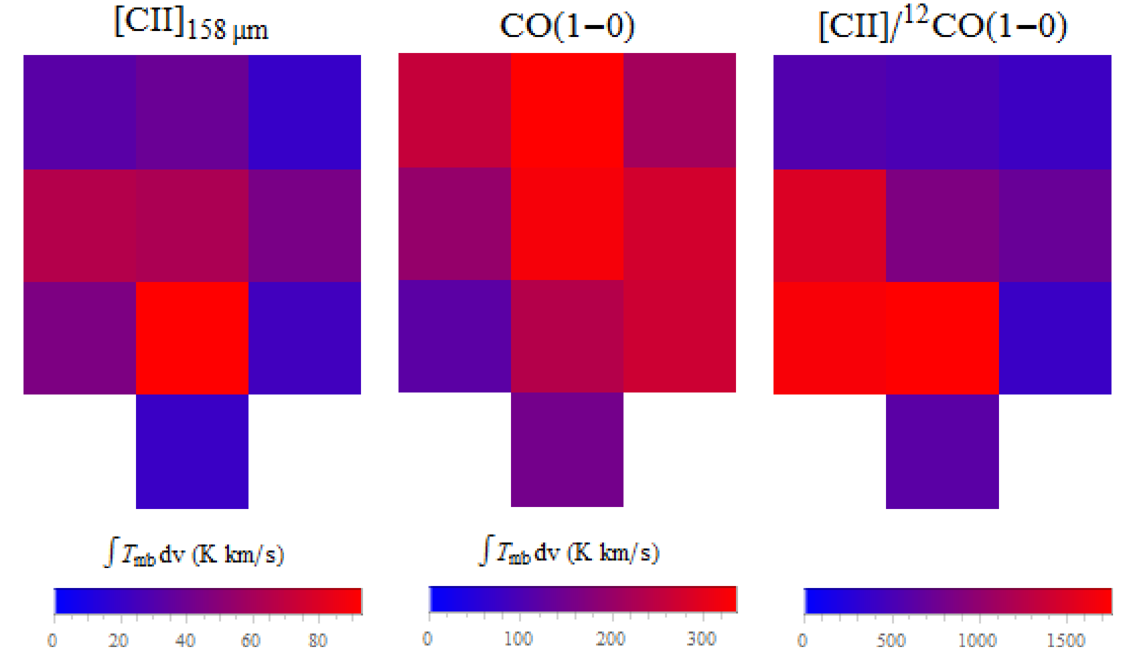
KAO compared to SOFIA



- [CII] and CO emission has a significantly different area filling factor
- C^+ has wider distribution.
- CO is concentrated toward the cool, shielded portion of the ISM
- Diffuse clouds with very little CO and much C^+ fill up the beam.

- With higher angular resolution we expect the [CII]/CO ratio to decrease.

Results from the 2014 flights: [CII]/CO



Direct comparison of line integrated intensities (single-component):

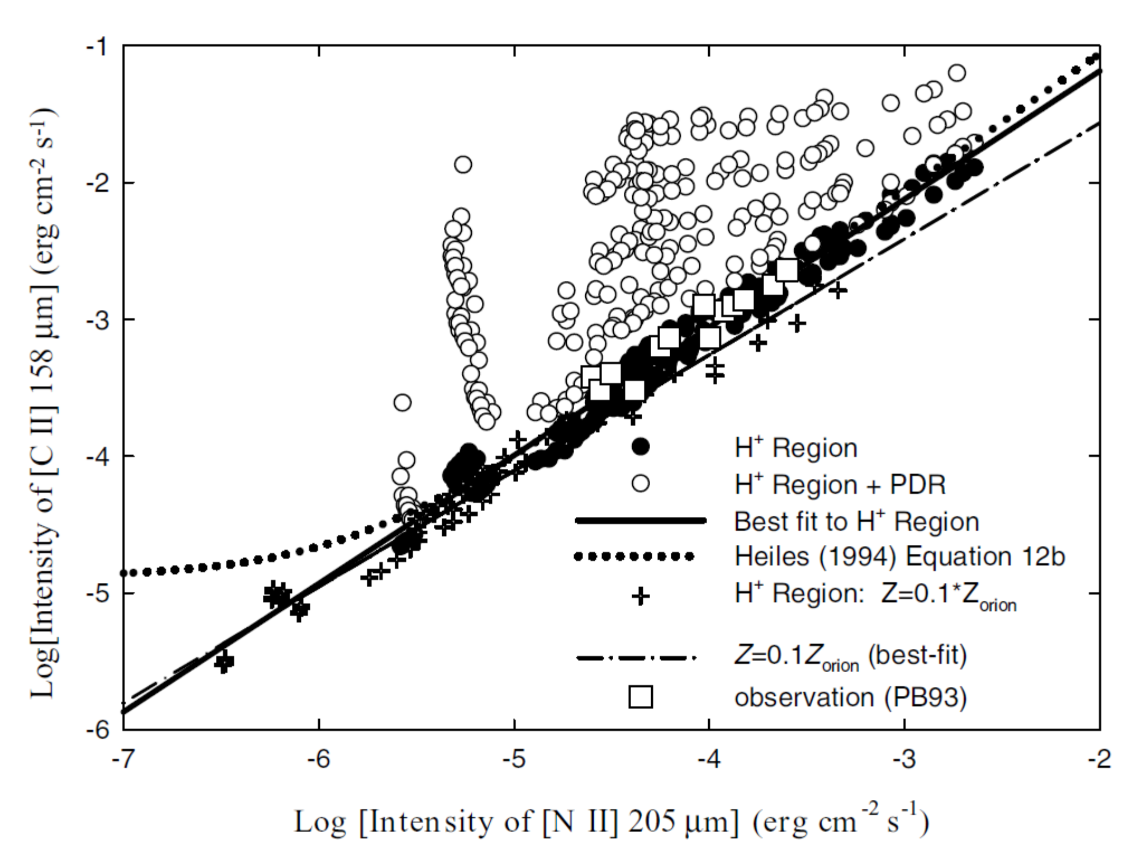
- [CII] emission strongest in the S-E quadrant
- [CII]/CO ratio highest in the S-E of our 3x3 grid.
- Local variations in the [CII]/CO ratio indicate spatial variations of the PDR/star formation activitiy along the molecular ring and mini-spiral.

[CII] – [NII] correlation

- IP(N) = 14.53 eV
- FUV energy in PDRs 6eV<hν<13.6 eV
- **[NII] is always emitted from HII regions**

- IP(C) = 11.3 eV
- Carbon in HII regions is in the form C^+ and C^{2+}
- Carbon in PDRs is layered C^+/C/CO
- **[CII] is emitted from PDRs and HII regions**

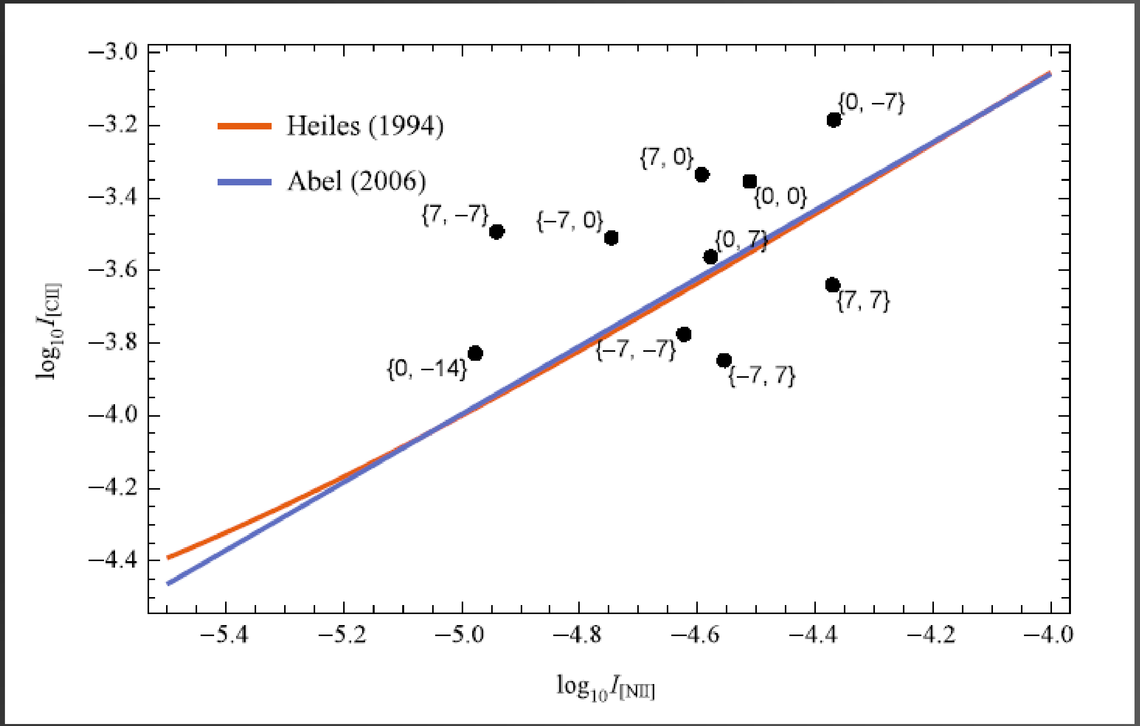
What fraction of [CII] is from which phase?



Abel 2006

[CII] – [NII] correlation in IC 342

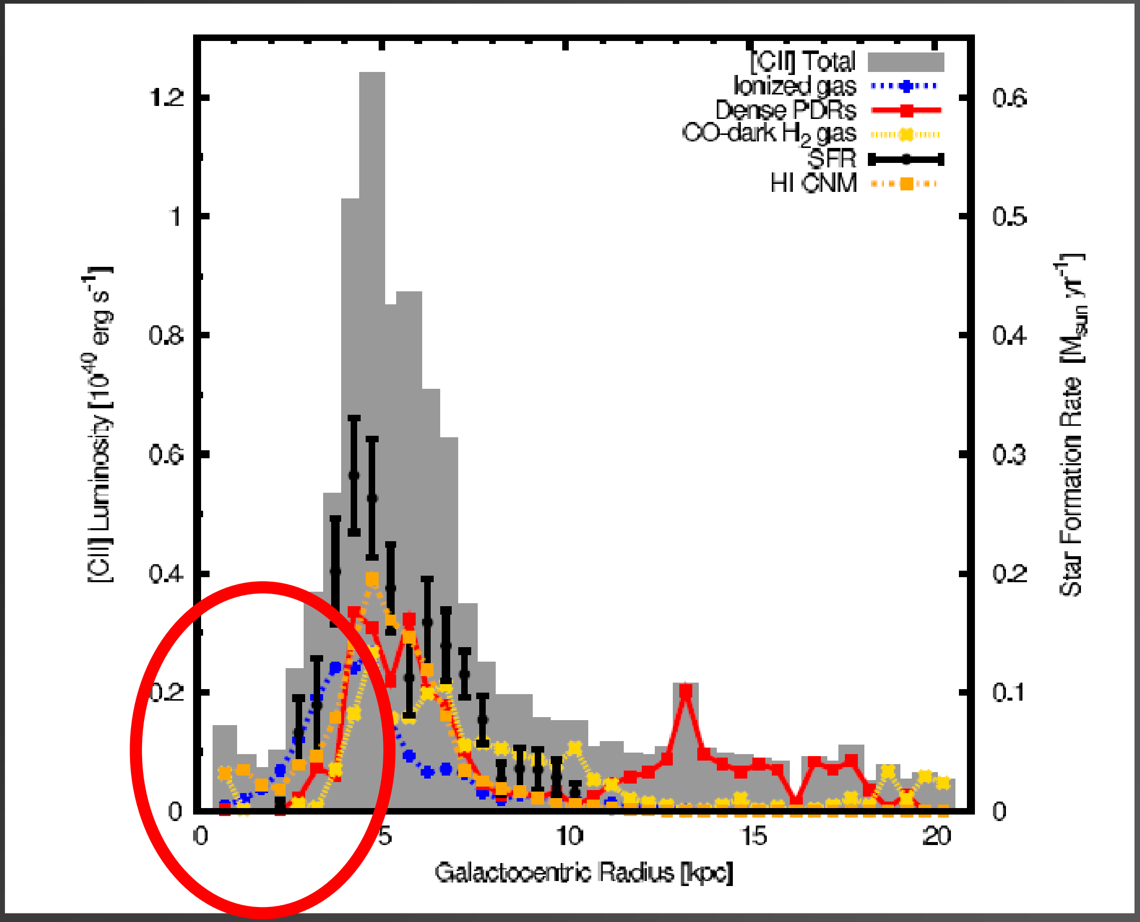
- 3 positions: only $[CII]_{HII}$
- 7 positions: $[CII]_{HII}$~ 40-90% $[CII]_{tot}$
- Quite high values:
  MW average $[CII]_{HII}$~ 20%, $[CII]_{PDR}$~30%



[CII] – [NII] correlation in IC 342

- 3 positions: only $[CII]_{HII}$
- 7 positions: $[CII]_{HII}$~ 40-90% $[CII]_{tot}$
- Quite high values:
  MW average $[CII]_{HII}$~ 20%, $[CII]_{PDR}$~30%
- But: inner kpc of the MW also shows
  $[CII]_{HII}$ > $[CII]_{PDR}$

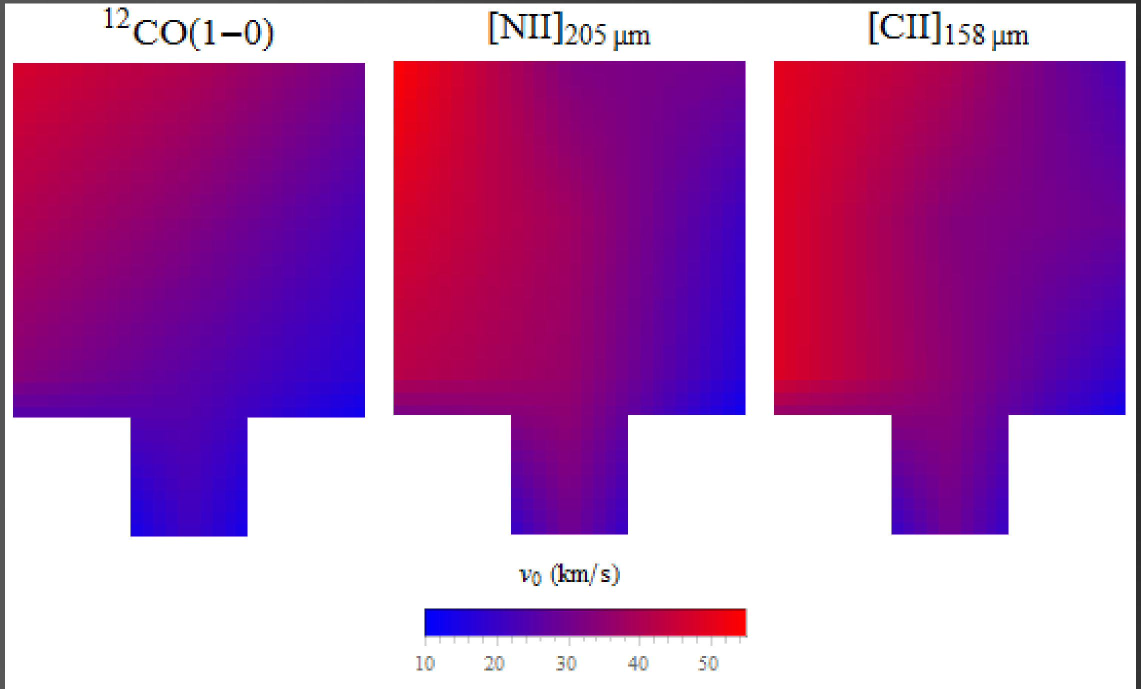
- Both, IC 342 and MW show a strong contribution of $[CII]_{HII}$ to $[CII]_{tot}$



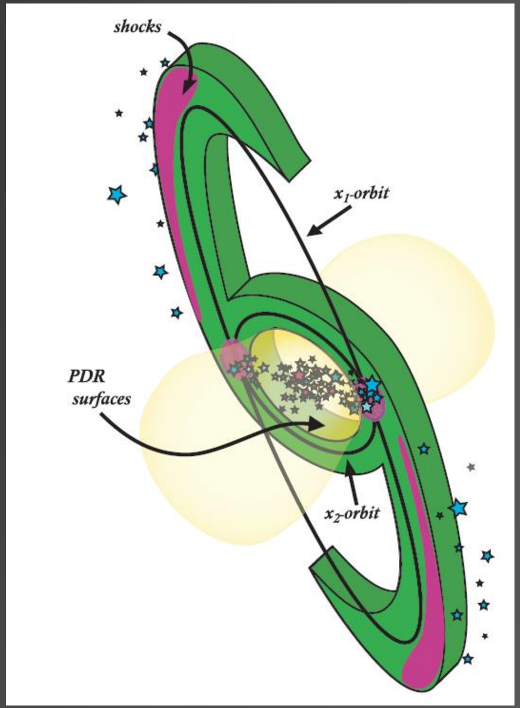
Pineda et al. 2014

Kinematics: [CII], [NII] and ^{12}CO(1-0)

line center velocities

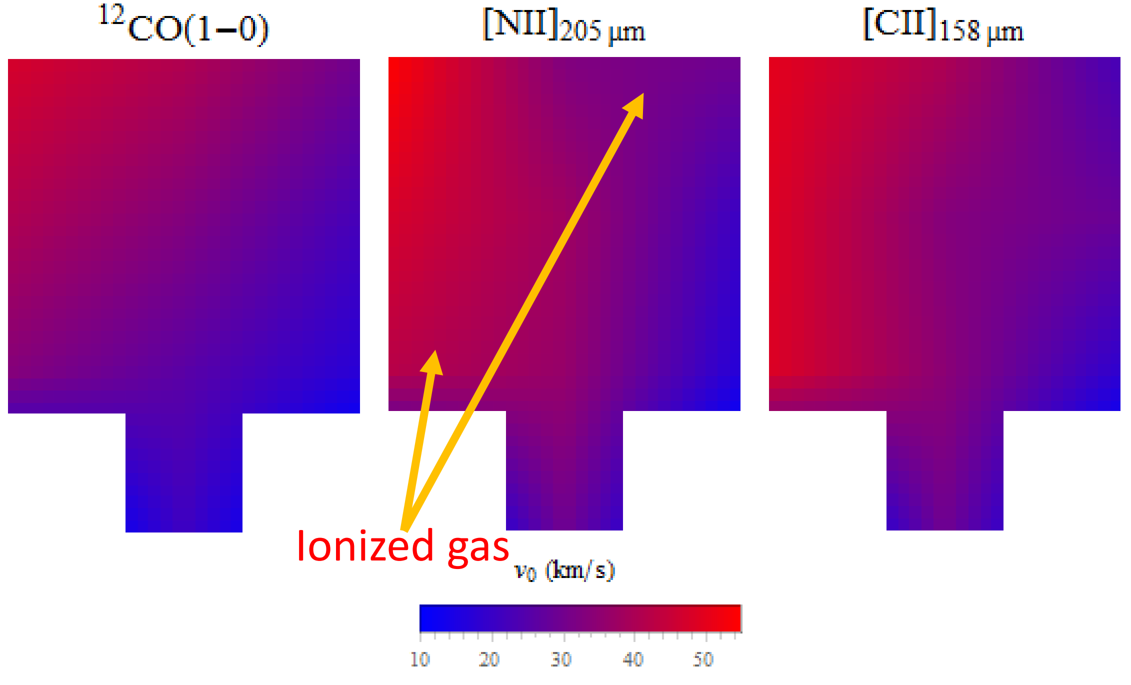


- Gaussian line center velocities show spatial differences between CO, C$^+$ and N$^+$
- CO shows a clear velocity gradient from N-E to S-W

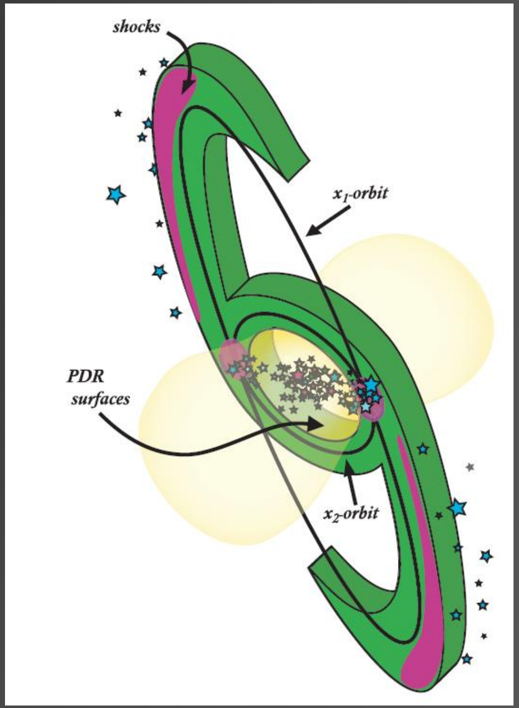


Kinematics: [CII], [NII] and ^{12}CO(1-0)

line center velocities

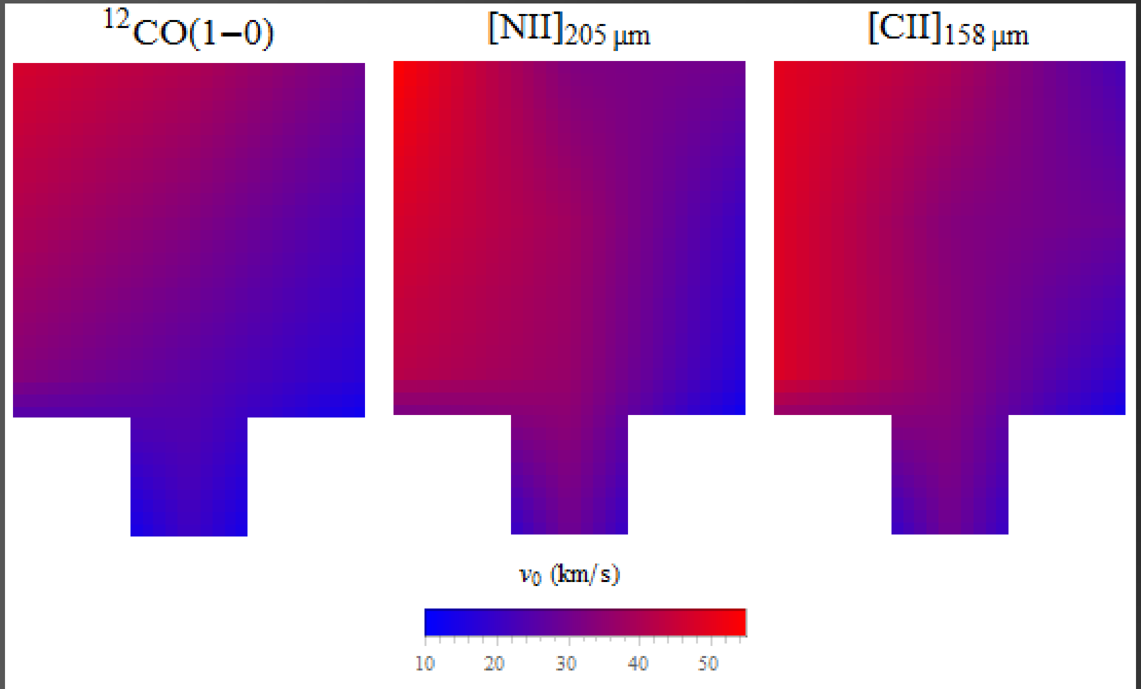


- Gaussian line center velocities show spatial differences between CO, C$^+$ and N$^+$
- CO shows a clear velocity gradient from N-E to S-W

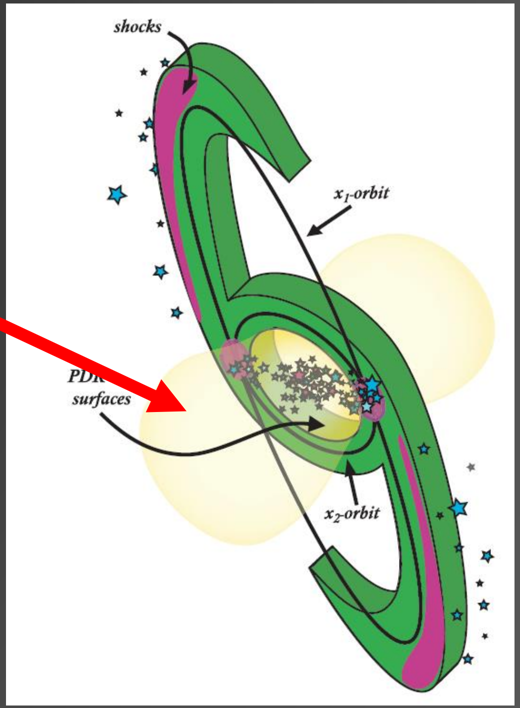


Kinematics: [CII], [NII] and $^{12}CO(1\text{-}0)$

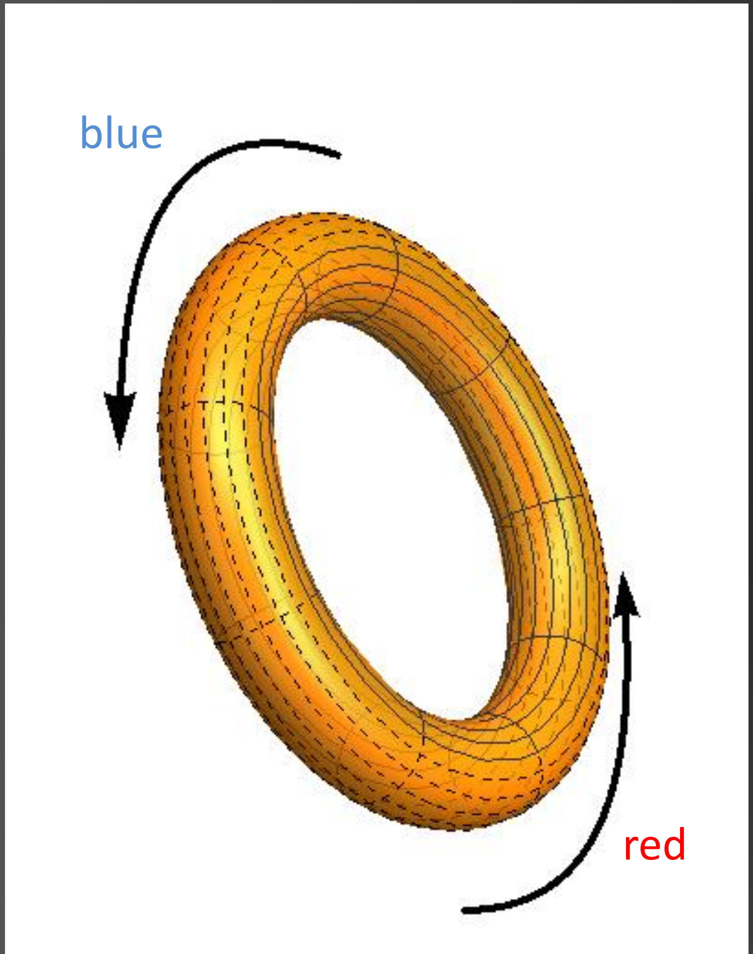
line center velocities



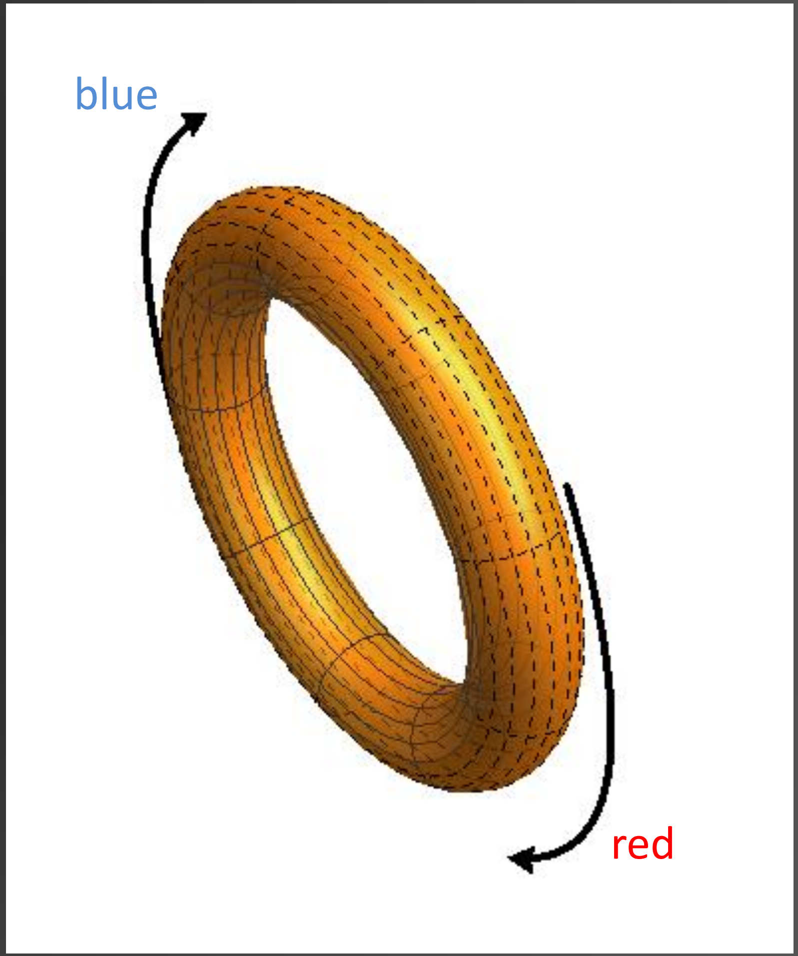
- Gaussian line center velocities are show spatial differences between CO, C^+ and N^+
- CO shows a clear velocity gradient from N-E to S-W
- BUT: This N^+ gas should be blue-shifted!



Ambiguity due to projection

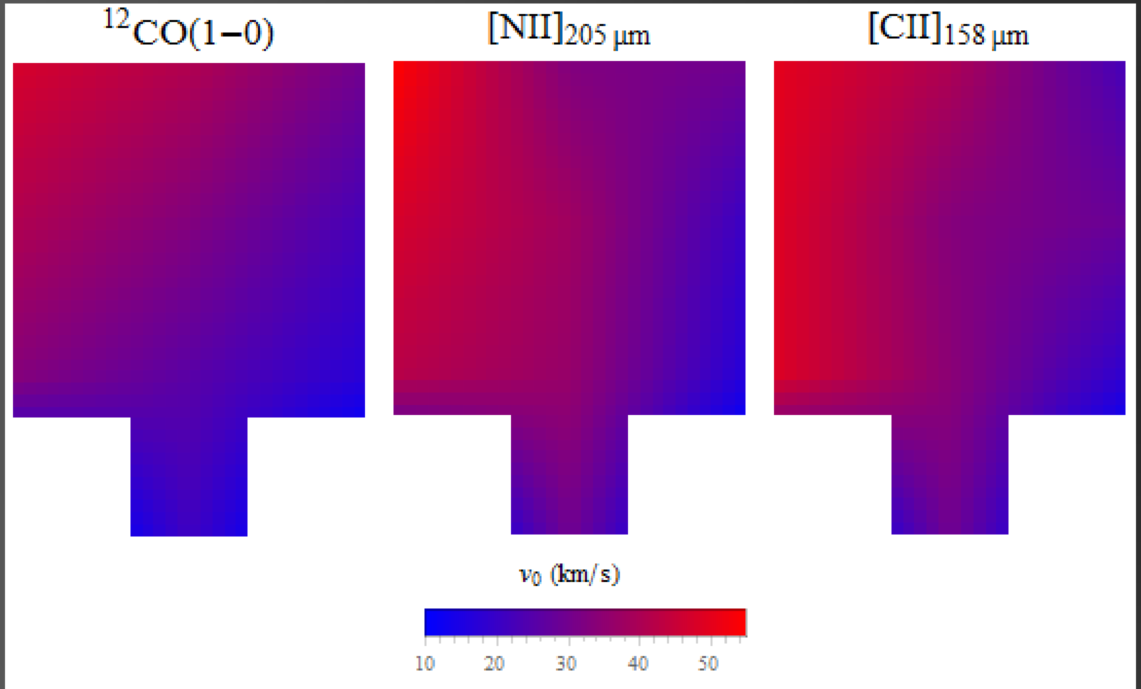


2 possible orientations of the plane

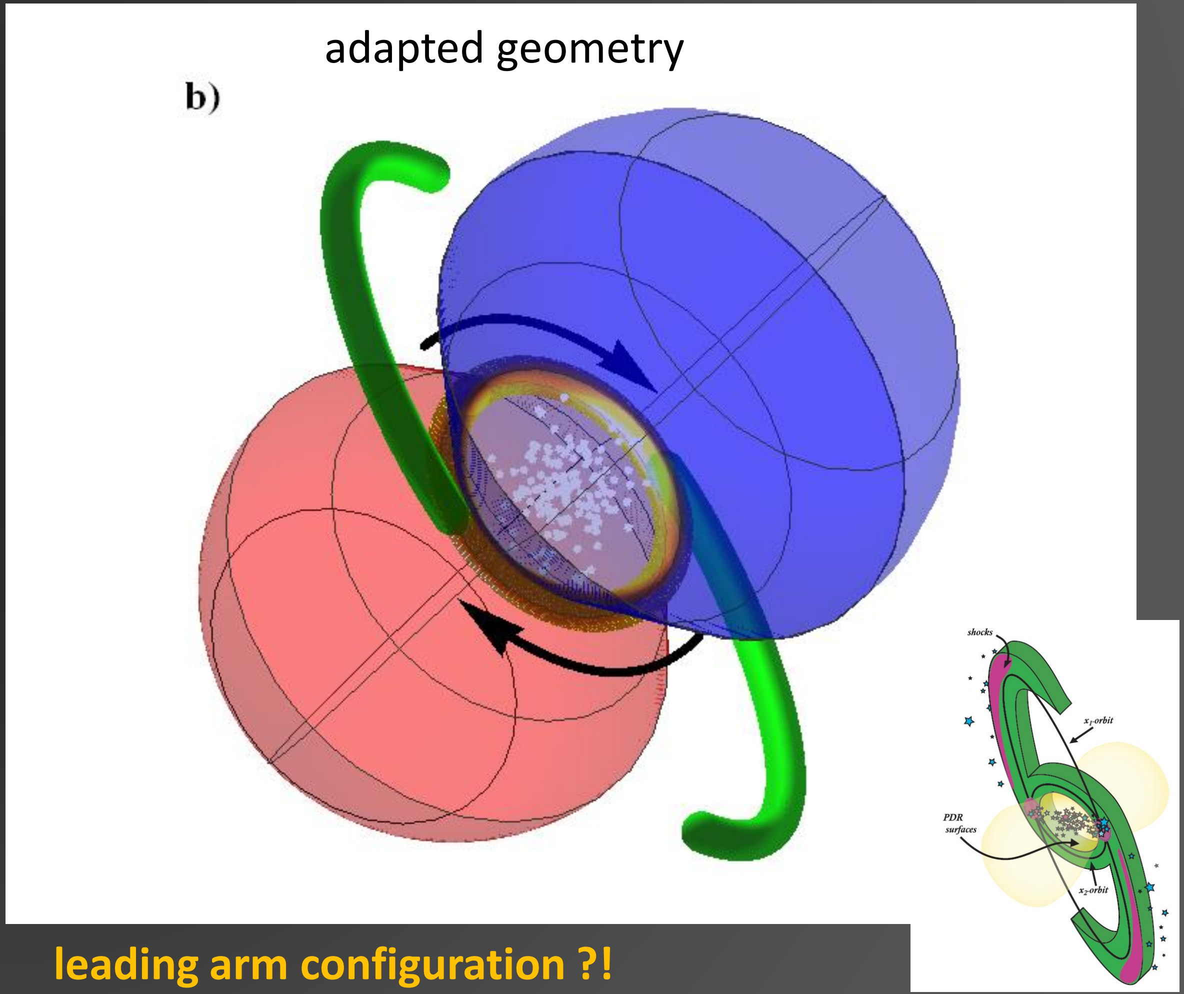


Kinematics: [CII], [NII] and ^{12}CO(1-0)

line center velocities



Doppler-shift of ionized gas leads to an update of the geometrical model of the nucleus of IC 342.



leading arm configuration ?!

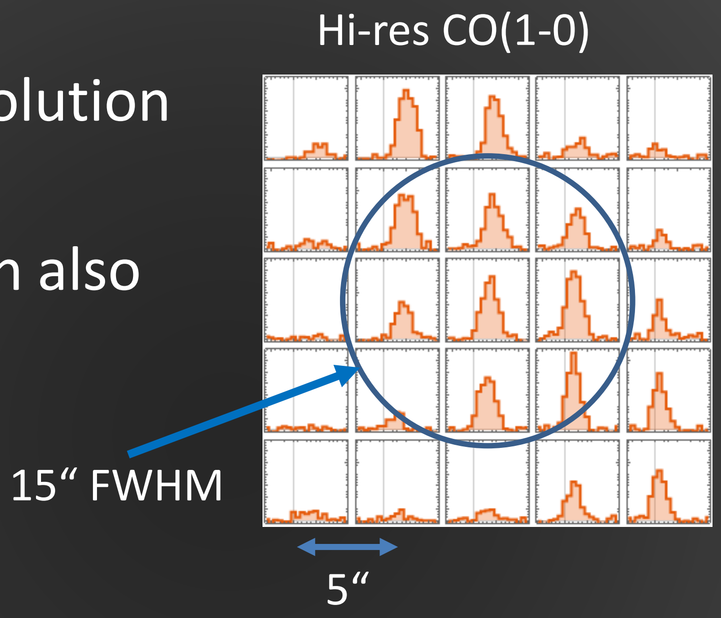
Super-resolution simulation

- The 15“ SOFIA [CII] beam corresponds to   D>240pc
- The unresolved GMCs, PDRs, etc. in the beam pass their kinematic signature on to the observed, beam convolved [CII] spectrum.
- If we had access to kinematic information with higher angular resolution, we could analyze how the unresolved structures need to be distributed to result in the observed spectral line shape.
- There is no [CII] data with higher angular resolution.

- **But there is interferrometric CO data available with resolution ≤ 5“**

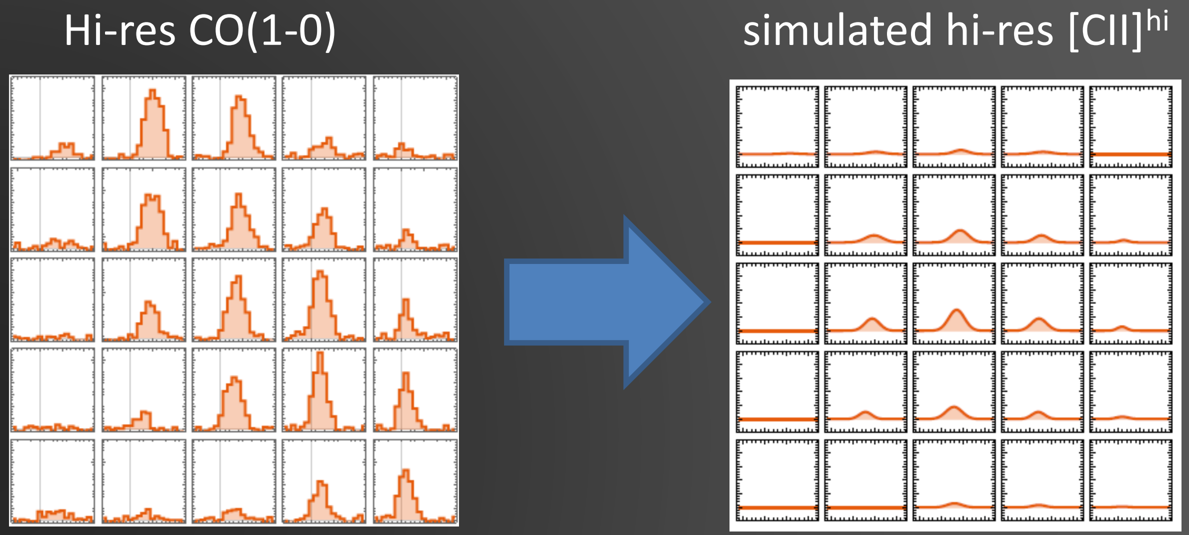
Sub-beam [CII]-CO correlation

- CO data with higher angular resolution than [CII] is available.
- We assume a [CII]-CO correlation also on very small scales.



Sub-beam [CII]-CO correlation

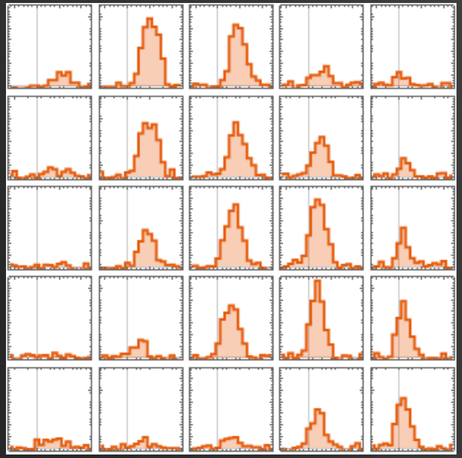
- CO data with higher angular resolution than [CII] is available.
- We assume a [CII]-CO correlation also on very small scales.
- We model artificial $[CII]^{hi}$ assuming $FWHM_{CO}$ and $v_{0,CO}$



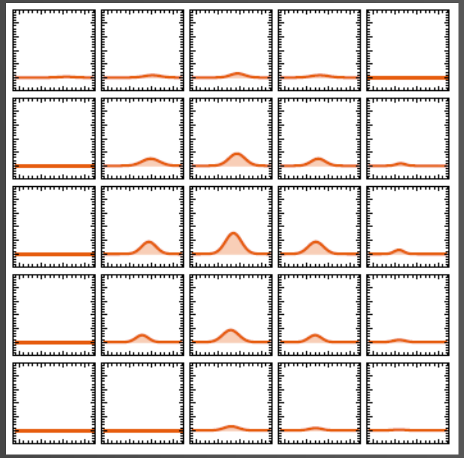
Sub-beam [CII]-CO correlation

- CO data with higher angular resolution than [CII] is available.
- We assume a [CII]-CO correlation also on very small scales.
- We model artificial $[CII]^{hi}$ assuming $FWHM_{CO}$ and $v_{0,CO}$
- Simulate observation by convolving with 15“ beam $[CII]^{hi}$ => $[CII]^{lo}$

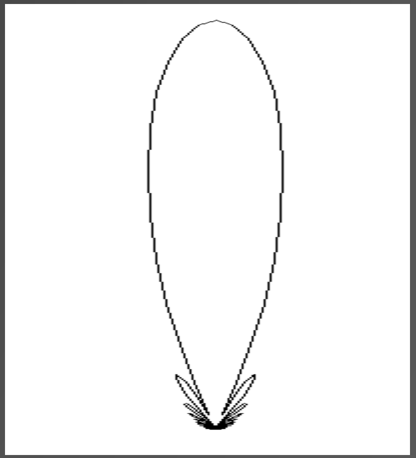
Hi-res CO(1-0)



simulated hi-res $[CII]^{hi}$



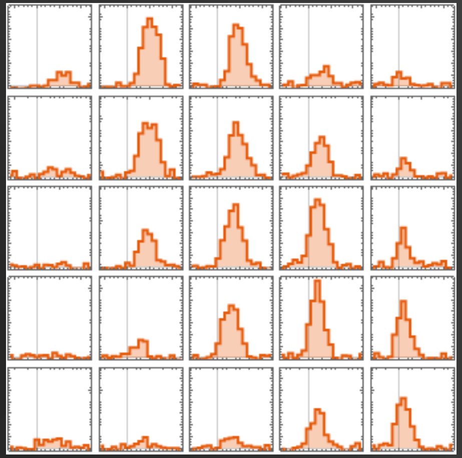
Convolve w. beam



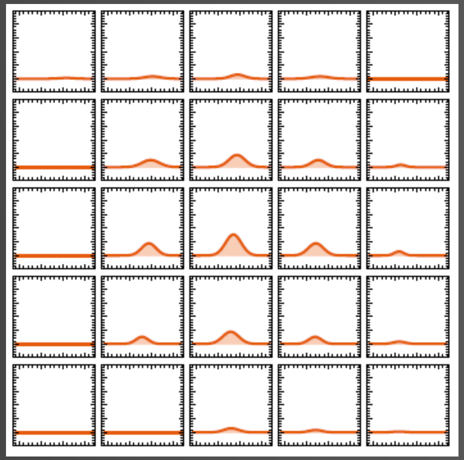
Sub-beam [CII]-CO correlation

- CO data with higher angular resolution than [CII] is available.
- We assume a [CII]-CO correlation also on very small scales.
- We model artificial $[CII]^{hi}$ assuming $FWHM_{CO}$ and $v_{0,CO}$
- Simulate observation by convolving with 15“ beam $[CII]^{hi}$ => $[CII]^{lo}$
- Compare beam convolved $[CII]^{low}$ with $[CII]_{obs}$

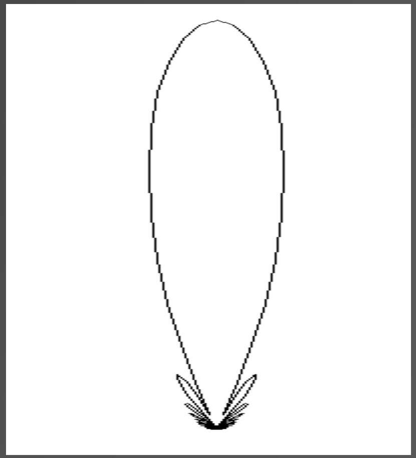
Hi-res CO(1-0)



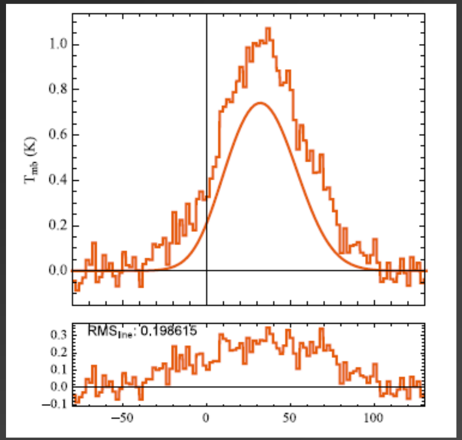
simulated hi-res $[CII]^{hi}$



Convolve w. beam

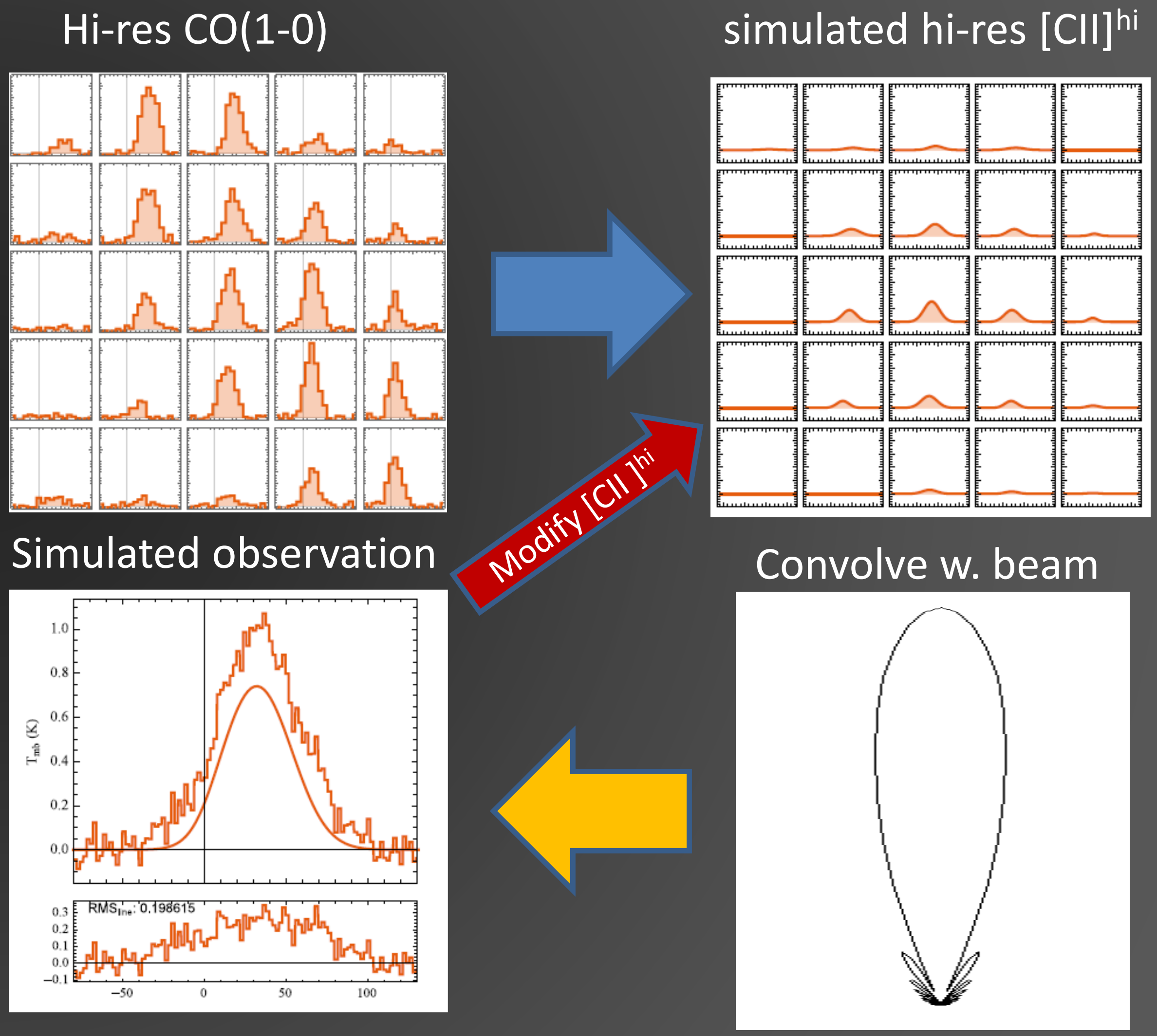


Simulated observation

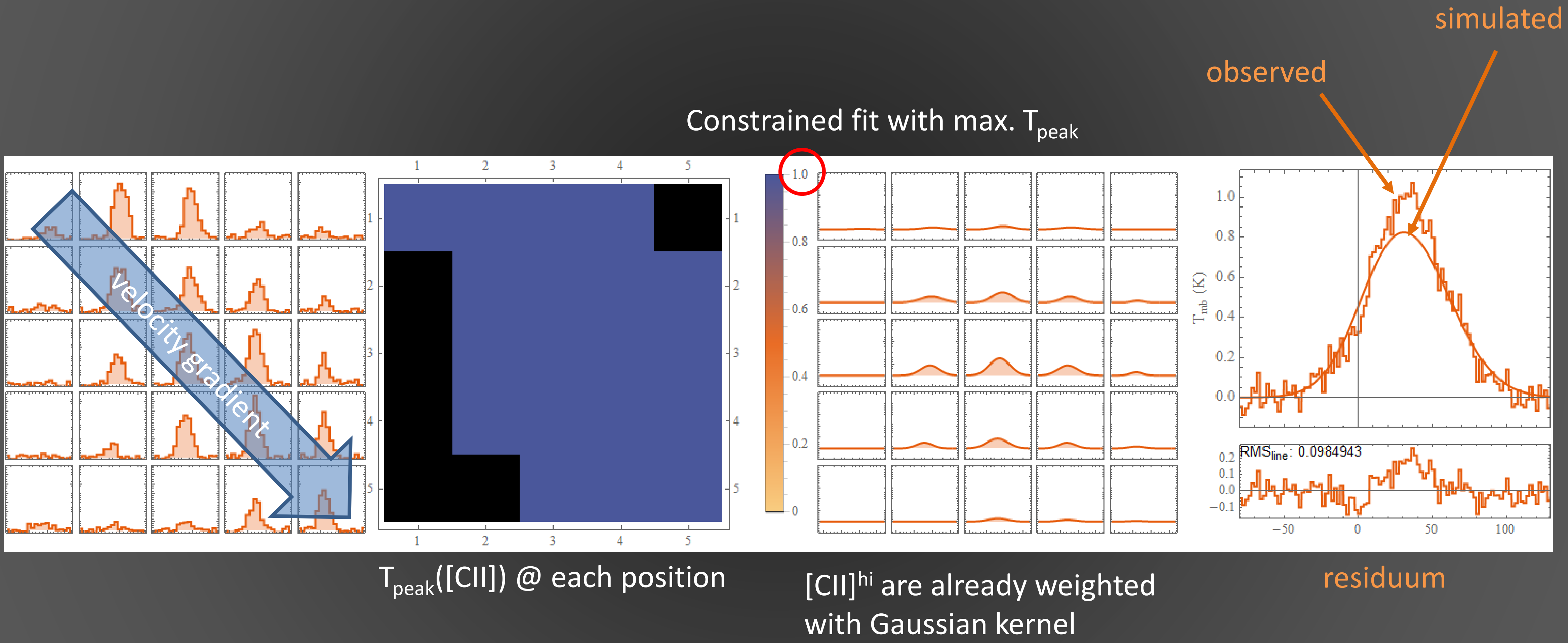


Sub-beam [CII]-CO correlation

- CO data with higher angular resolution than [CII] is available.
- We assume a [CII]-CO correlation also on very small scales.
- We model artificial $[CII]^{hi}$ assuming $FWHM_{CO}$ and $v_{0,CO}$
- Simulate observation by convolving with beam $[CII]^{hi}$ => $[CII]^{lo}$
- Compare beam convolved $[CII]^{low}$ with $[CII]_{obs}$
- Modify $[CII]^{hi}$
- Rinse and repeat

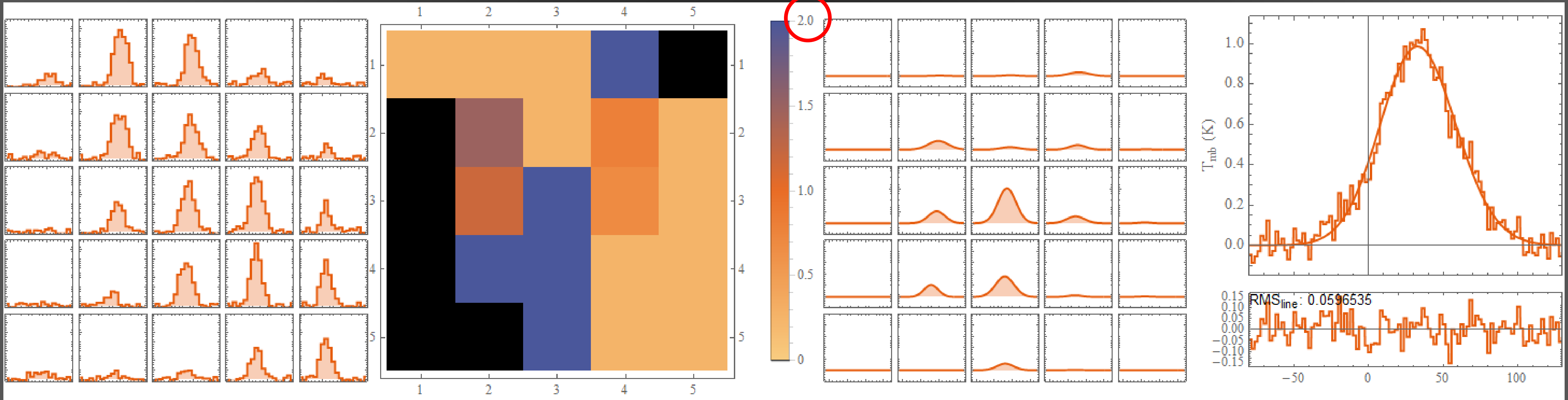


[CII] Super-Resolution Composition



[CII] Super-Resolution Composition

Constrained fit with max. T_{peak}



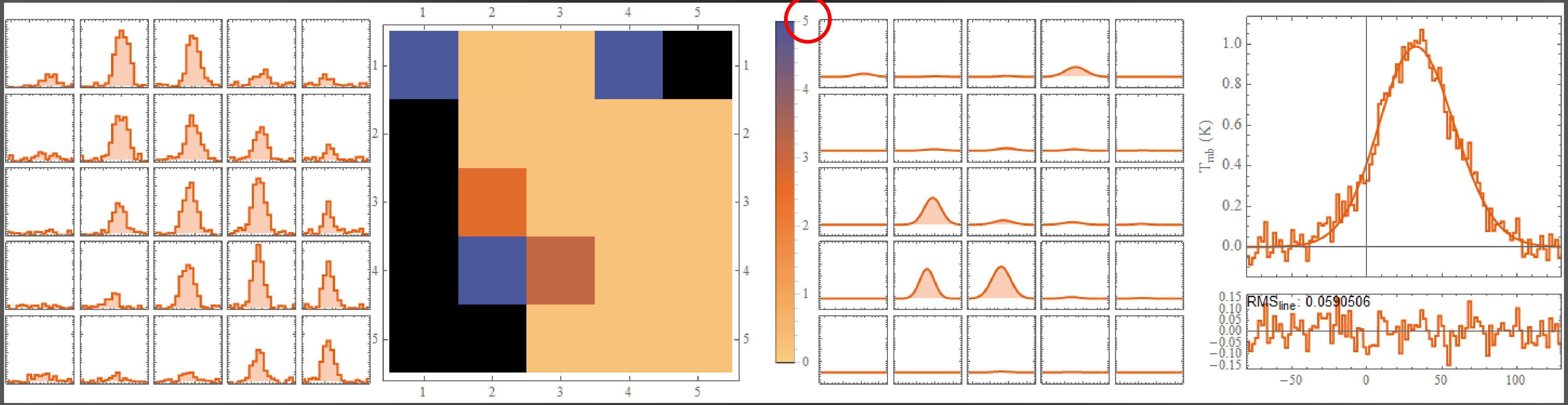
T_{peak}([CII]) @ each position

[CII]^{hi} are already weighted with Gaussian kernel

residuum

[CII] Super-Resolution Composition

Constrained fit with max. T_{peak}



T_{peak}([CII]) @ each position

[CII]^{hi} are already weighted with Gaussian kernel

residuum

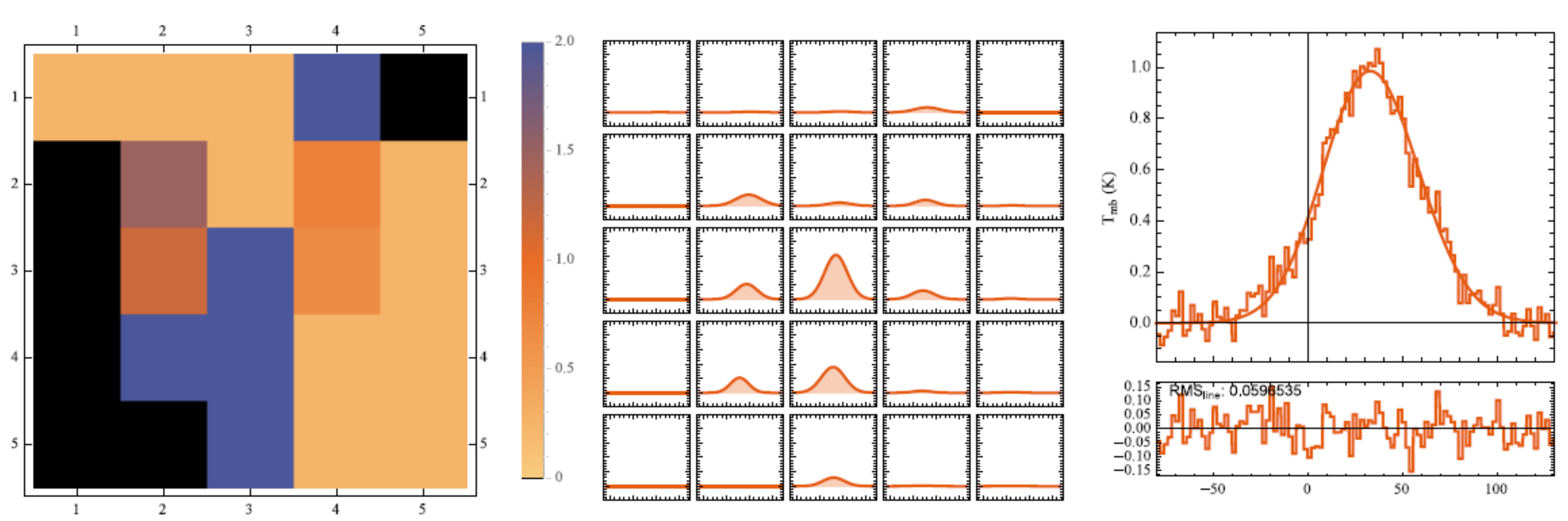
[CII] Super-Resolution Composition

- Numerical fitting with 25(+1) degrees of freedom of varying weight is challenging
- The weaker the velocity gradient across the CO-map is, the higher the degeneracy between the parameters
  $\rightarrow$ kinematic influence of one CO position can be substituted by other positions with matching line shape.
- Qualitative conclusions difficult $\rightarrow$ the initial goal of a super-resolved map of numeric [CII]/CO ratios not yet reached.
- Quantitative conclusions already possible

  $\rightarrow$ We find the same qualitative trends in the super-resolved [CII]/CO distribution with complementary methods

[CII] Super-Resolution Composition

- The kinematics of the observed [CII] emission is consistent with a scenario where the lower-left quadrant of the spiral/ring structure is dominantly contributing to the total [CII] emission. The gas along the northern arm is kinematically speaking of much less influence.



Summary

- $[CII]_{158\mu m}$ and $[NII]_{205\mu m}$ detected in the nucleus of IC 342
- The high angular and spectral resolution reveals a complex distribution of quiescent gas and PDR/starburst activity in the region.
- Strong starburst/PDR activity in the S-E consistent with complementary studies
- The kinematic information of the emission from the ionized gas leads us to a refined geometrical concept of the center region of IC 342 (leading vs. trailing arms)
- Super-resolution method can be used to convolve the kinematic information from correlated data with very high-res. into a simulated observation in order to gain additional knowledge on the details of the assumed correlation.

Thank you!