# $[CII]_{158\mu m}$ and $[NII]_{205\mu m}$ emission in IC 342

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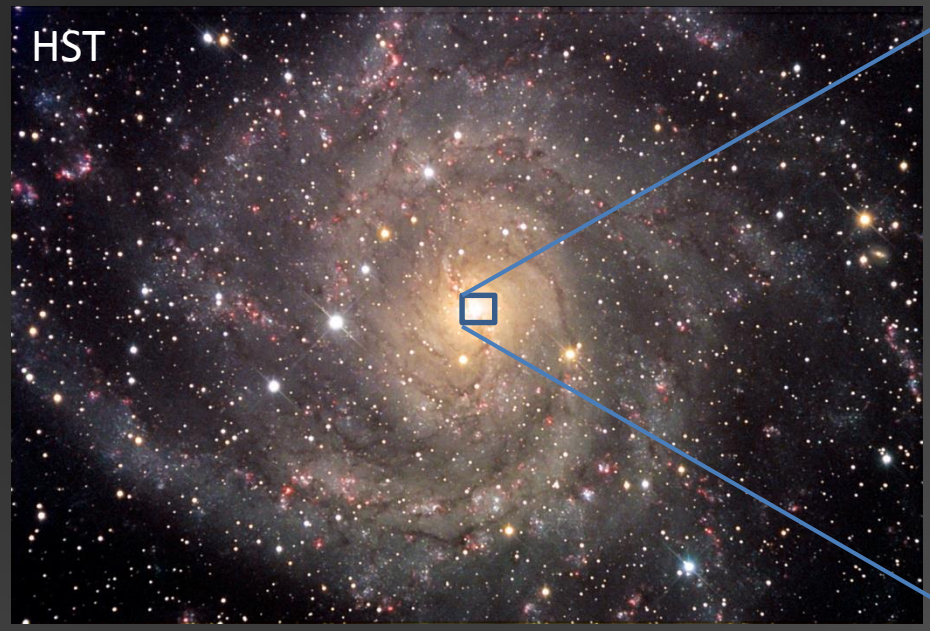
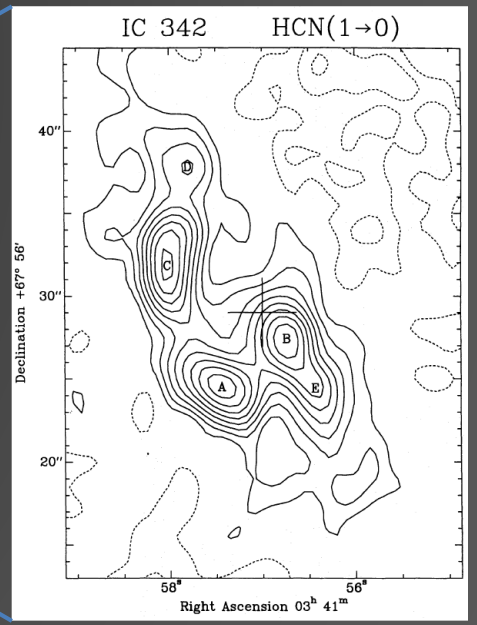
# Introduction


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

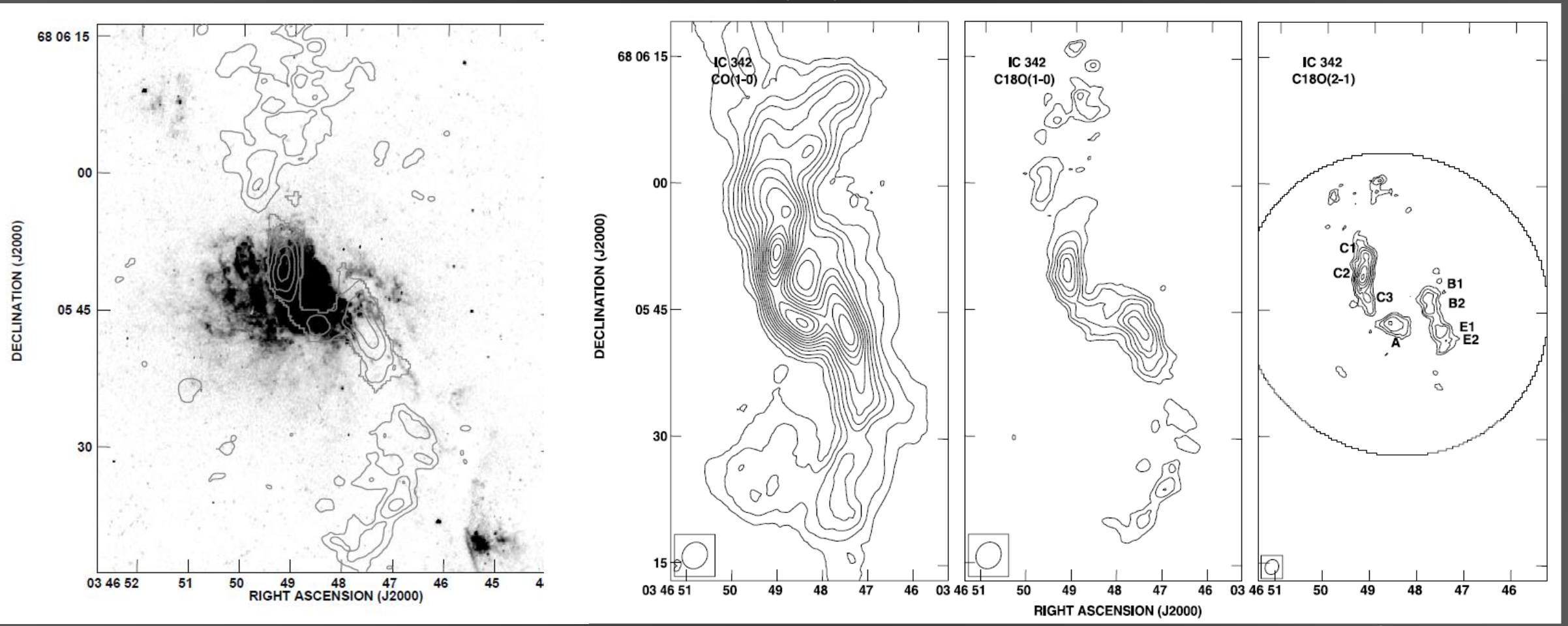



Downes et al. 1992

# The Nucleus of IC 342

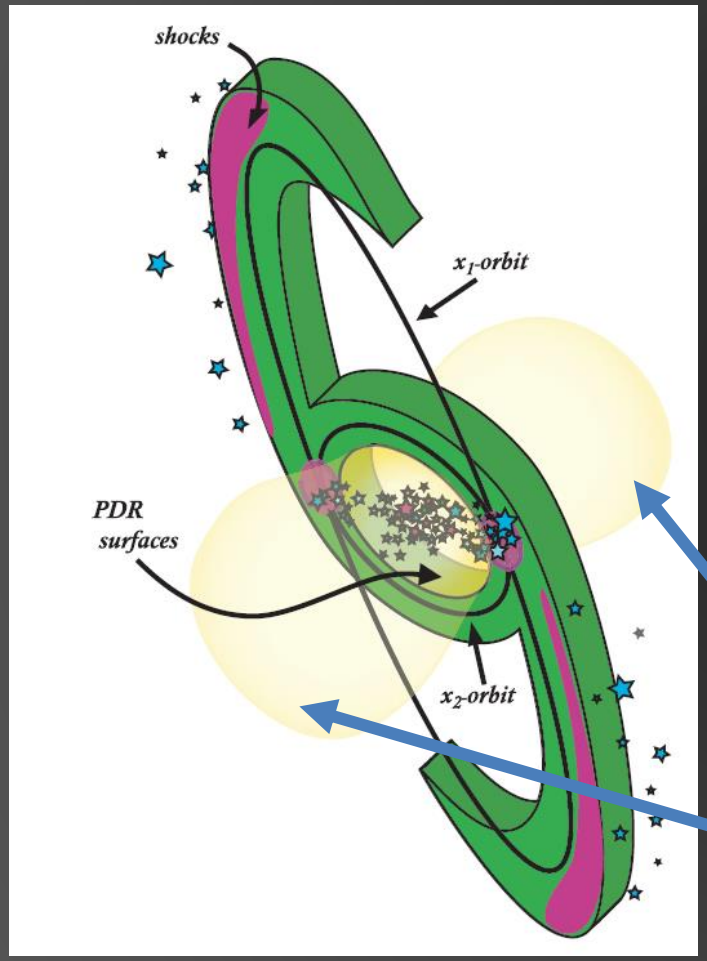
CO (1-0) $C^{18}O$ (1-0) $C^{18}O$ (2-1)




$N(H_2)$ on HST Hα

Meier & Turner 2001

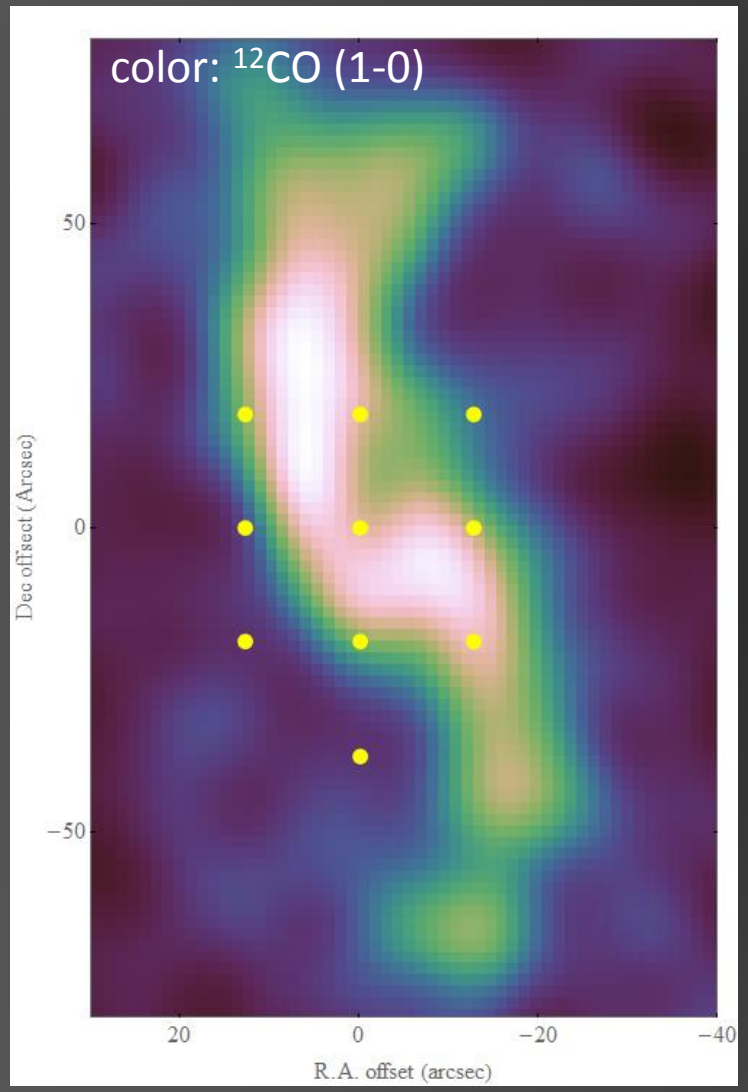
# IC 342 – Geometry of the inner 300pc




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 $\rightarrow$ PDR emission
- Expanding bubbles of HII gas

# 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

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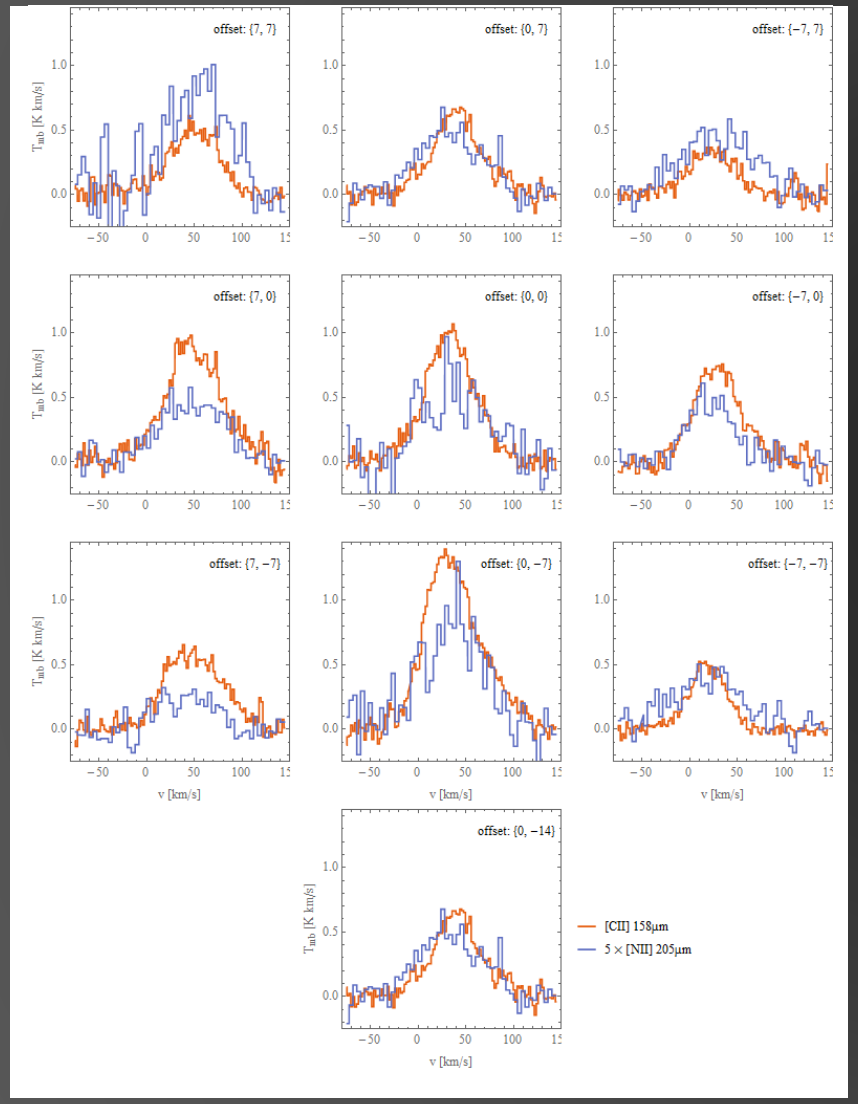


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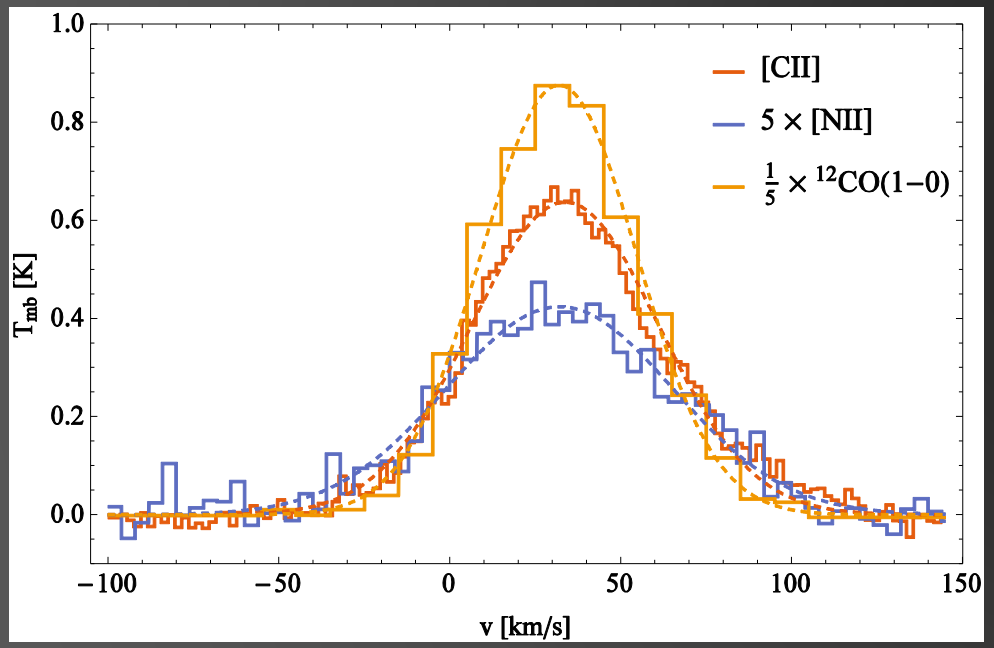
- $RMS_{[NII]}$<100mK

  $RMS_{[CII]}$<60mK

red: [CII], blue: [NII] ×5

# SOFIA/GREAT observations 2013/14

average spectrum over central 3x3

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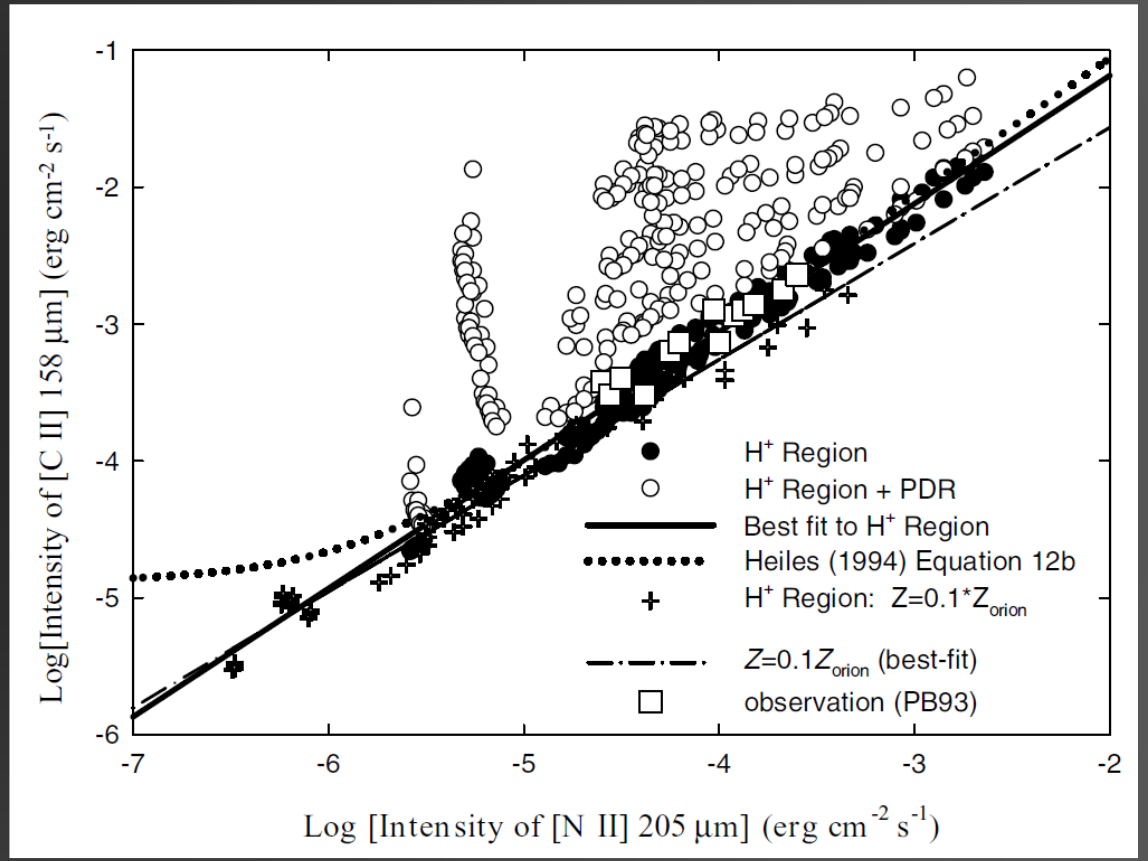
# [CII] – [NII] correlation

- IP(N) = 14.53 eV
- FUV energy in PDRs 6eV<hv<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

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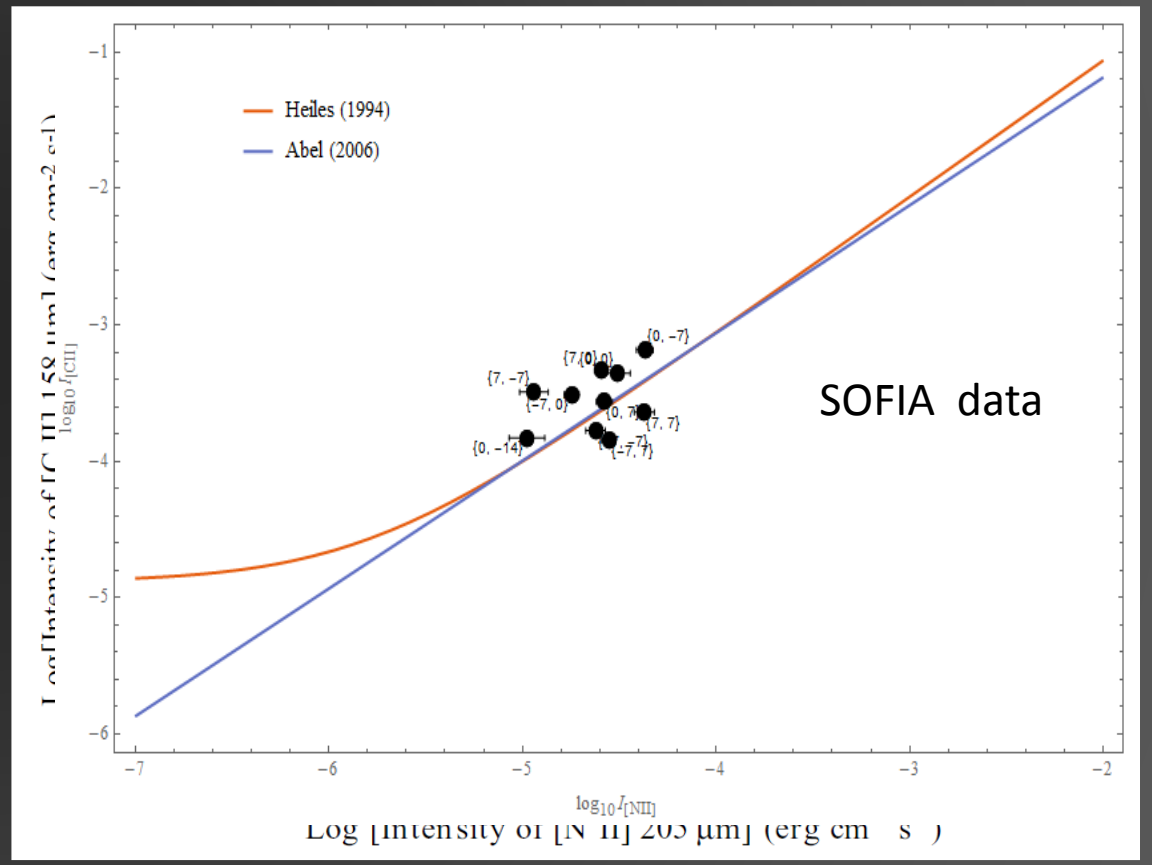
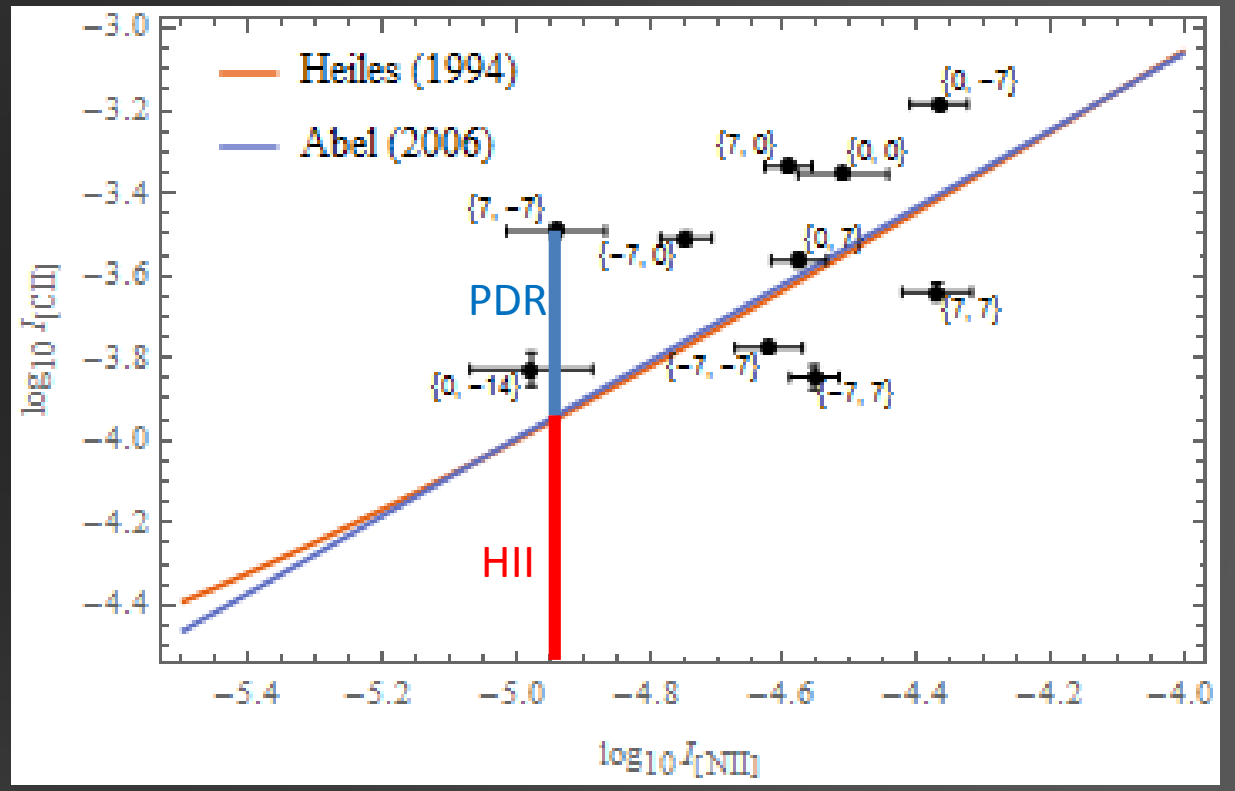



Abel 2006

# [CII] – [NII] correlation in IC 342

- 3 positions: only $[CII]_{HII}$
- 7 positions: $[CII]_{HII}$~ 35-90% $[CII]_{tot}$
- Quite high values:
  MW average $[CII]_{HII}$~ 20%, $[CII]_{PDR}$~30%




Röllig et al. 2015

# [CII] – [NII] correlation in IC 342

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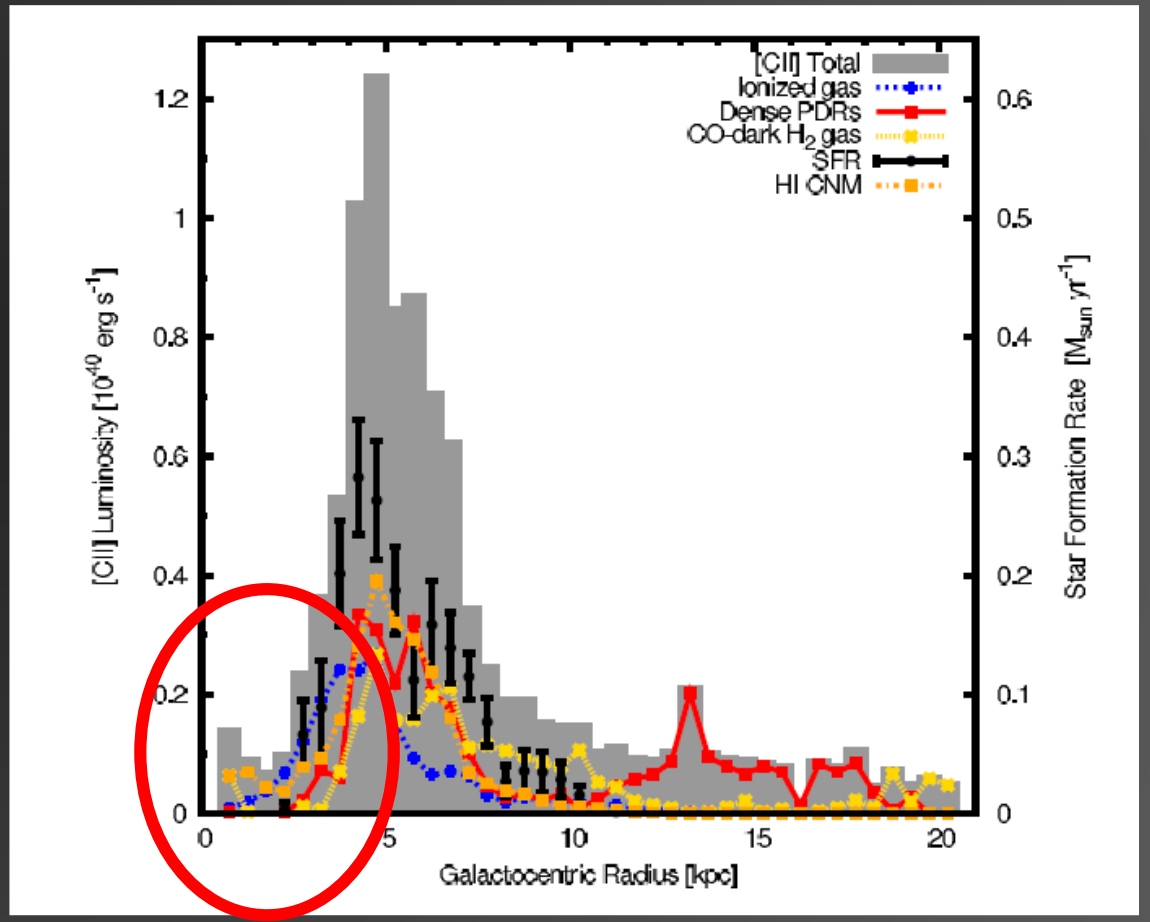
- 7 positions: $[CII]_{HII}$~ 35-90% $[CII]_{tot}$
- Quite high values:
  MW average $[CII]_{HII}$~ 20%, $[CII]_{PDR}$~30%
- But: inner kpc of the MW also shows
  $[CII]_{HII} > [CII]_{PDR}$

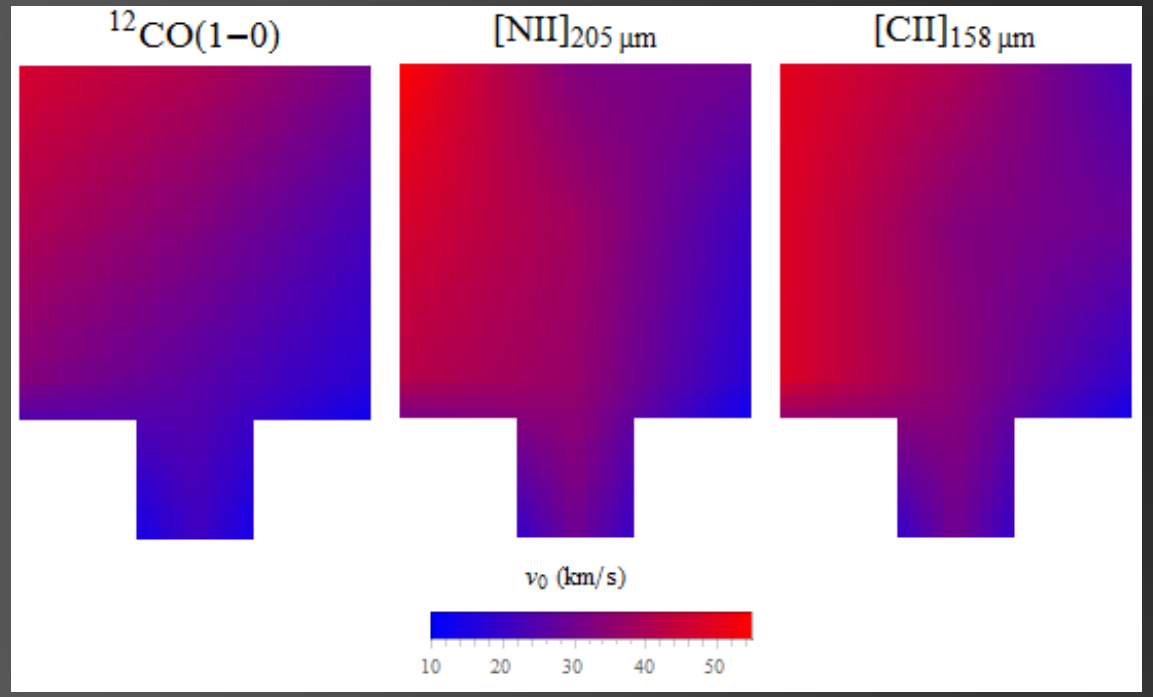
- Both, IC 342 and MW show a strong contribution of $[CII]_{HII}$ to $[CII]_{tot}$ in their center.



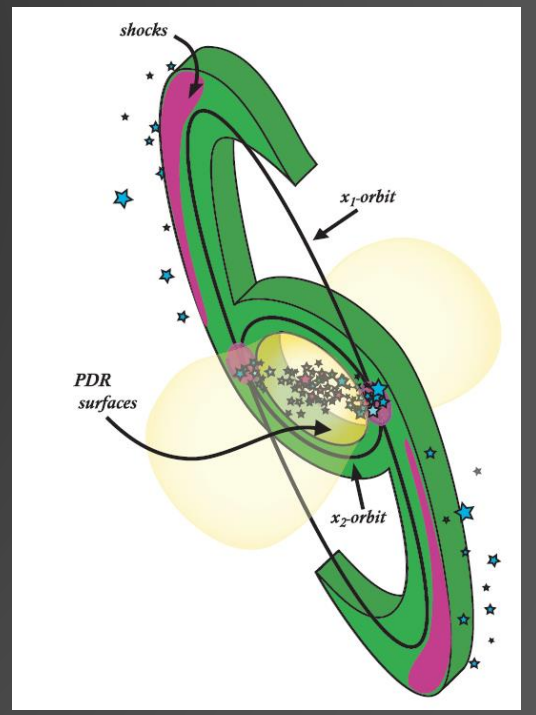

Pineda et al. 2014

# 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



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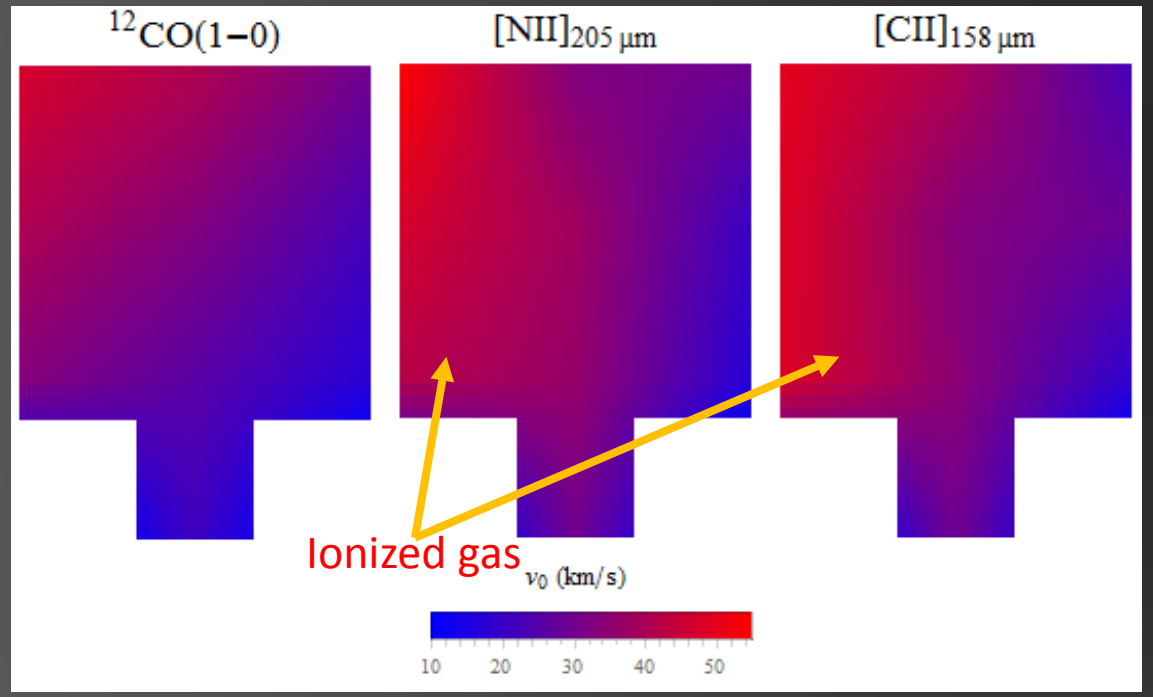


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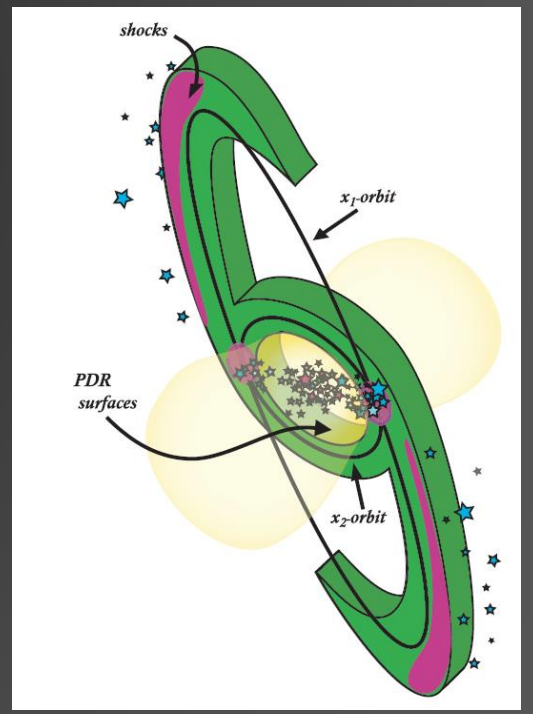

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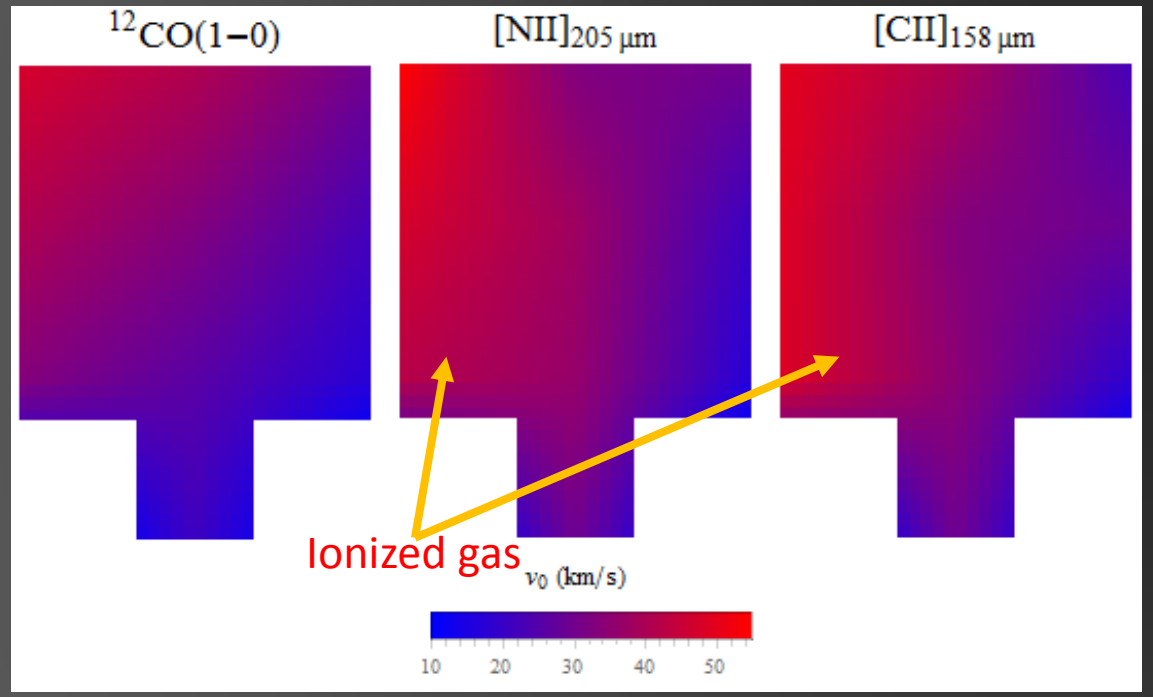
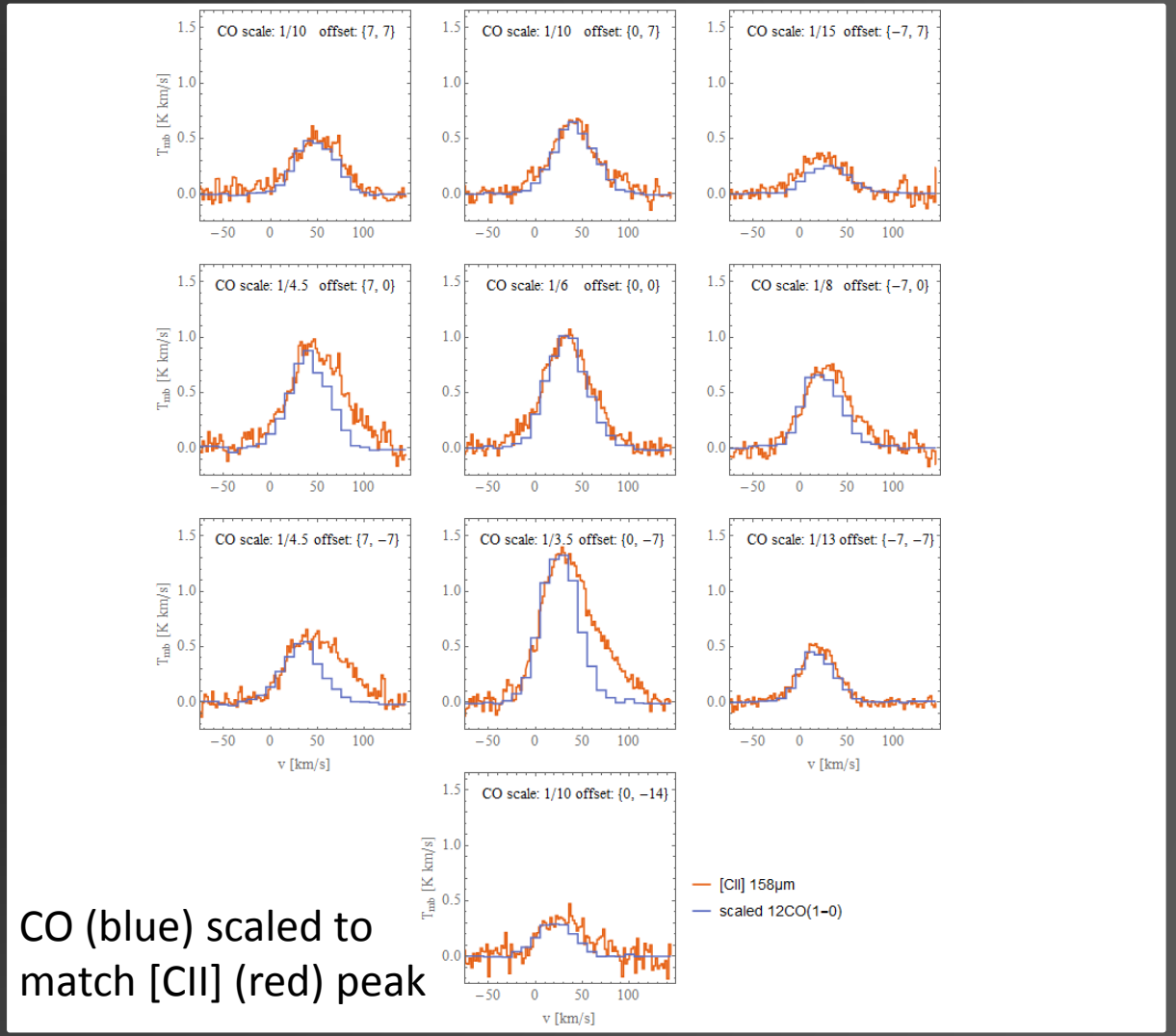
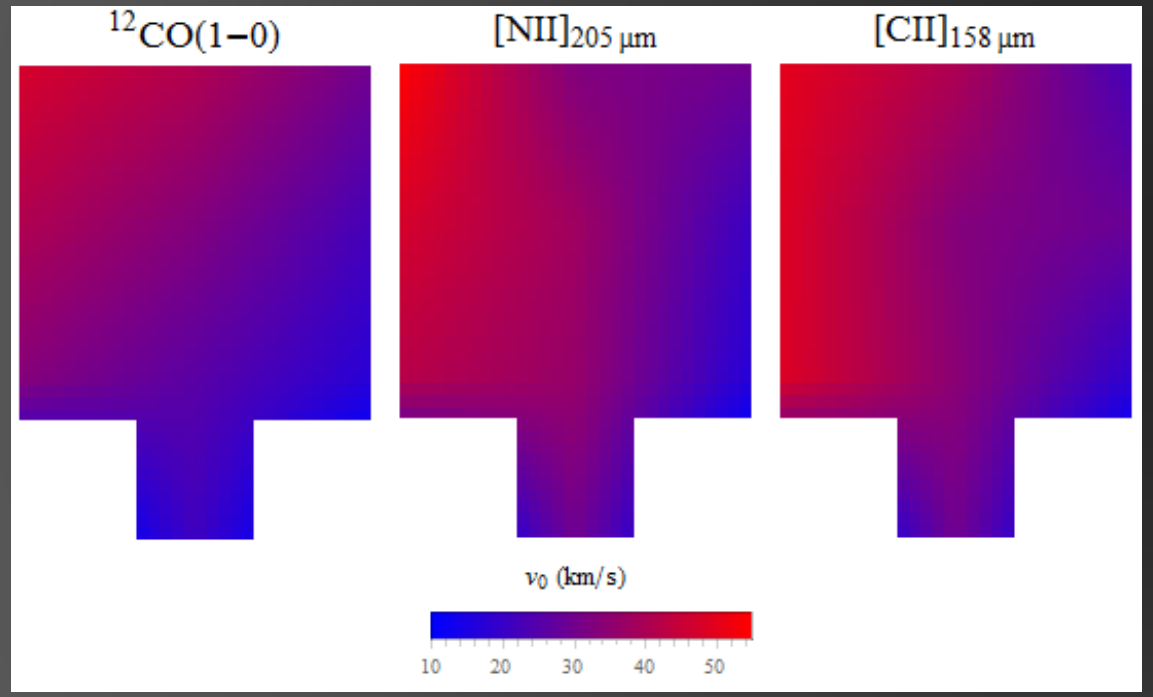


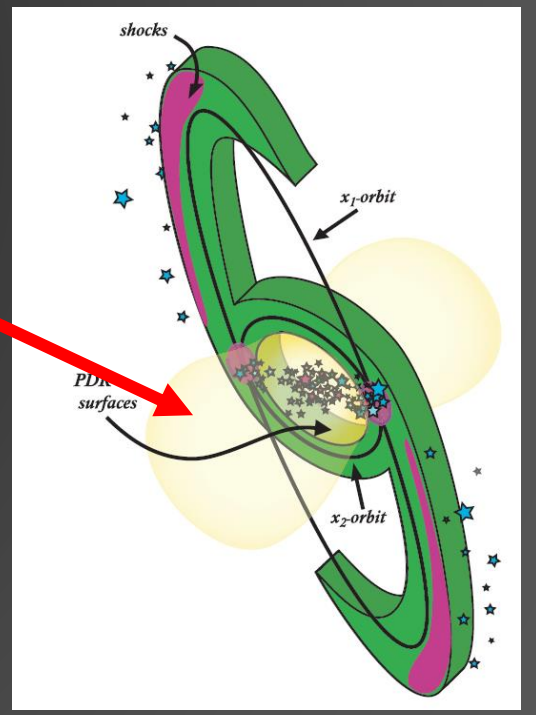

CO (blue) scaled to match [CII] (red) peak

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

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!



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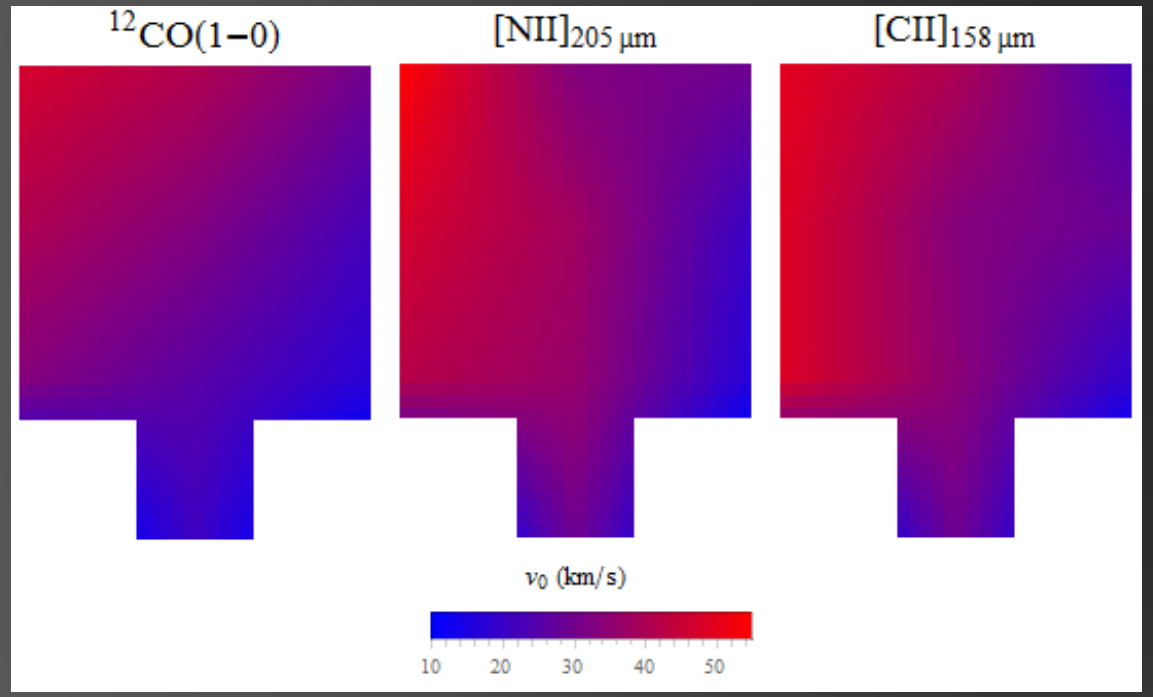
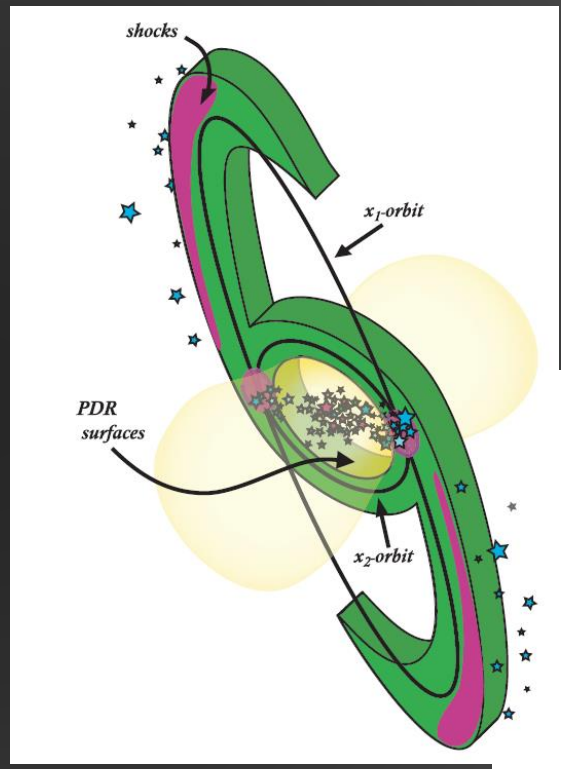
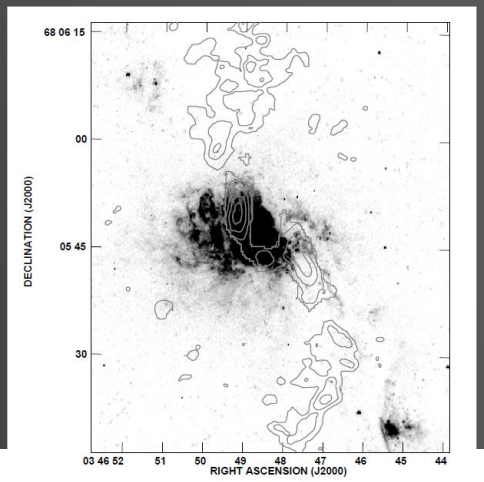
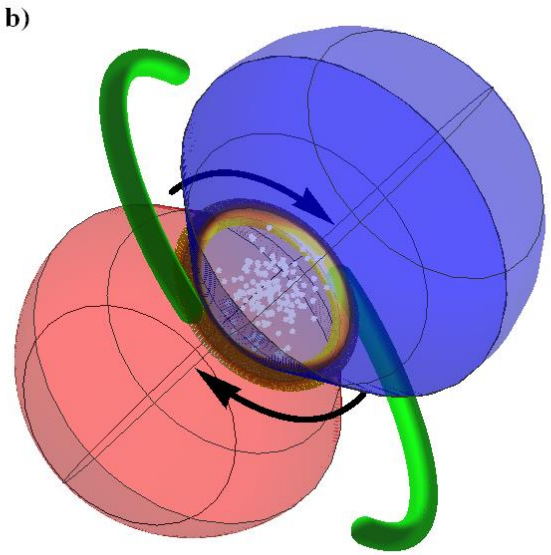



Doppler-shift of ionized gas challenges the geometrical model of the nucleus of IC 342.



**leading arm configuration ?!**

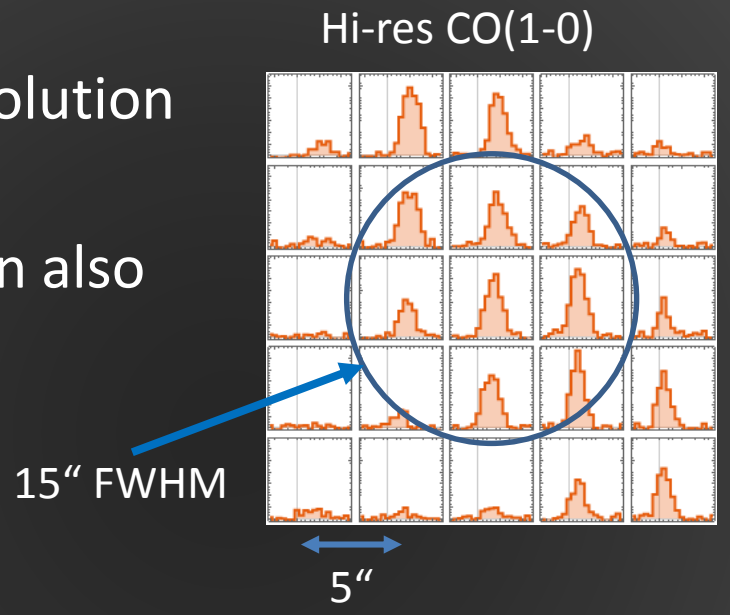
# Super-resolution simulation

- 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 interferometric 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.



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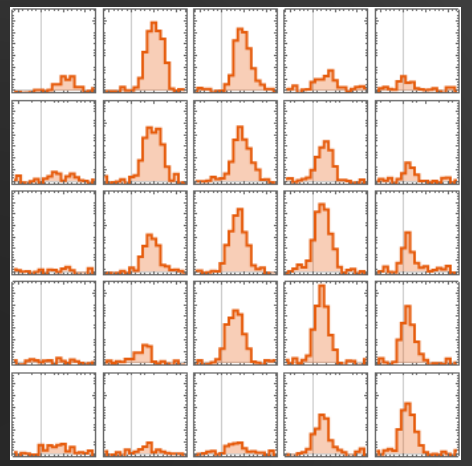
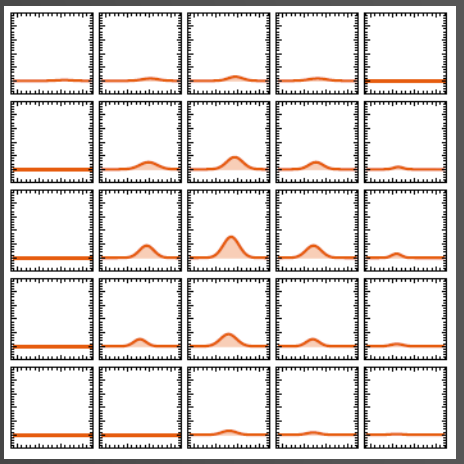
Hi-res CO(1-0)



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



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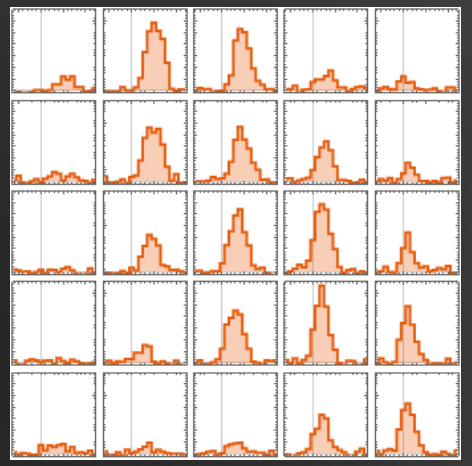

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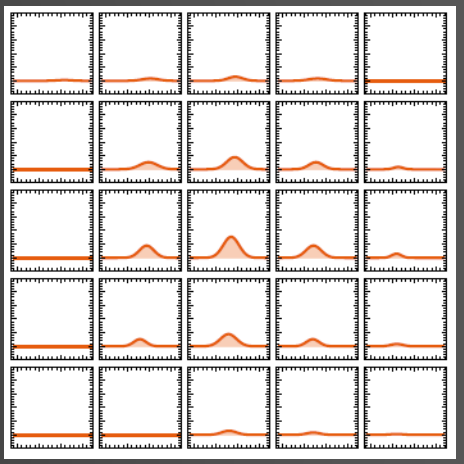
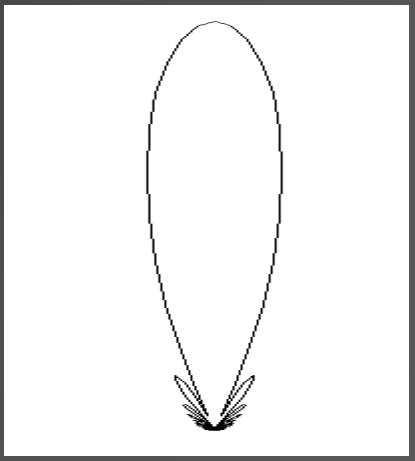


Convolve w. beam



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- Compare beam convolved $[CII]^{low}$ with $[CII]_{obs}$

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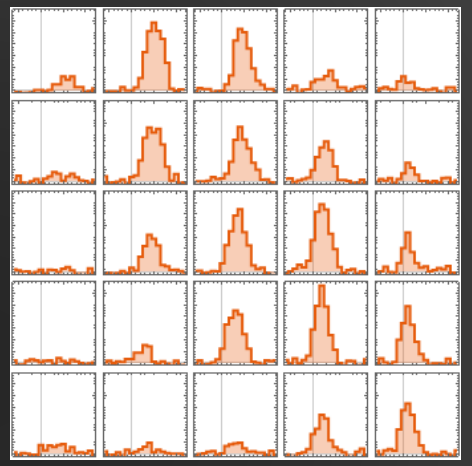

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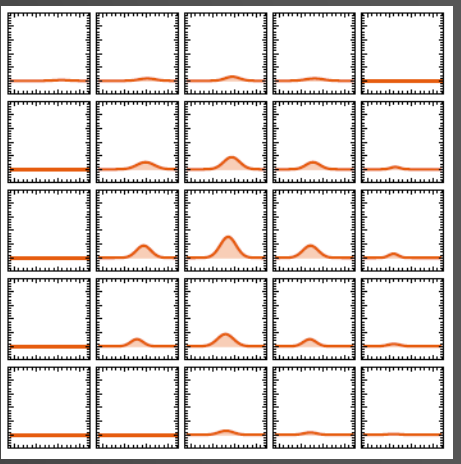
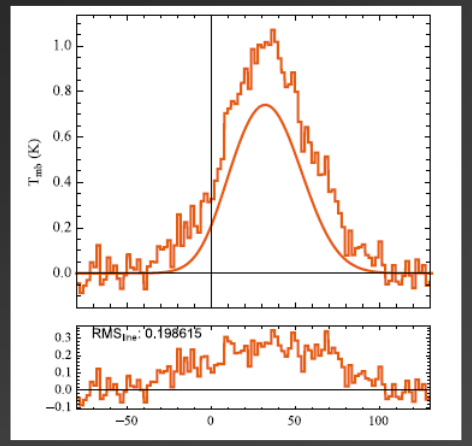


Simulated observation

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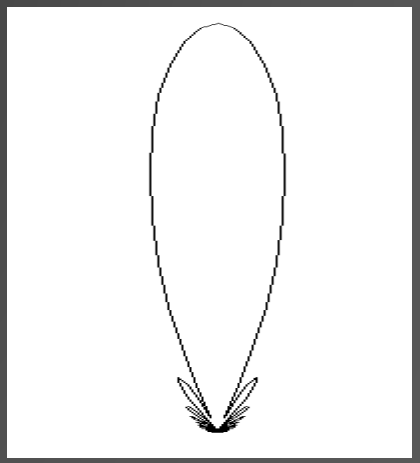

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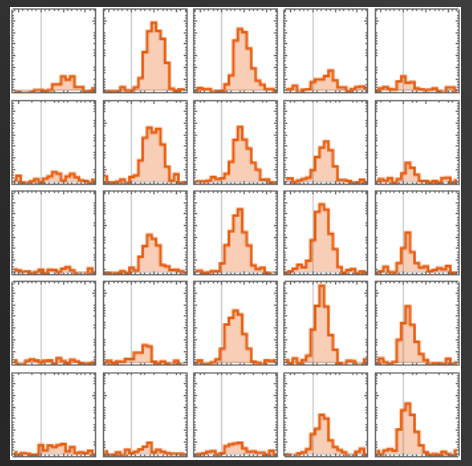
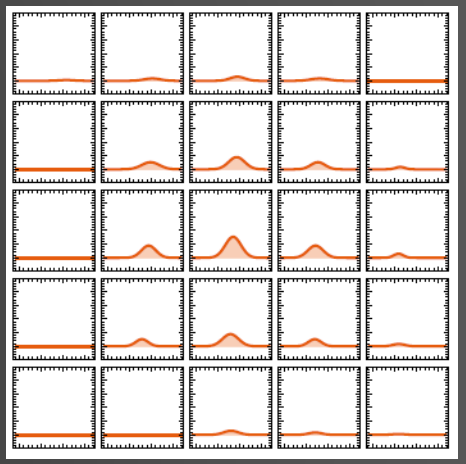
- Simulate observation by convolving with beam $[CII]^{hi\text{-}res}$ => $[CII]^{lo\text{-}res}$
- Compare beam convolved $[CII]^{lo\text{-}res}$ with $[CII]_{obs}$
- Modify $[CII]^{hi\text{-}res}$
- Rinse and repeat

Hi-res CO(1-0)

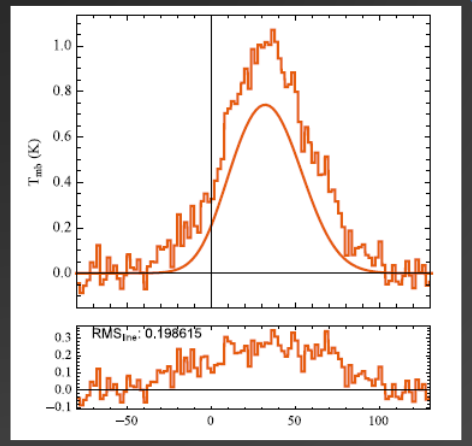


simulated hi-res $[CII]^{hi\text{-}res}$

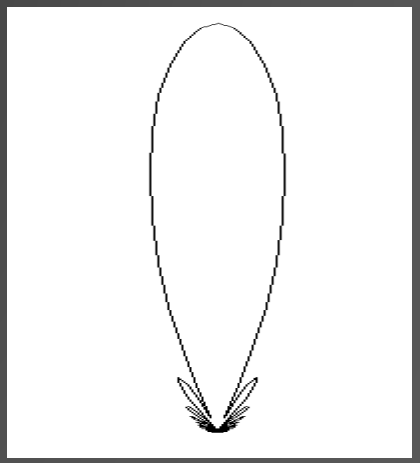


Modify $[CII]^{hi}$

Simulated observation

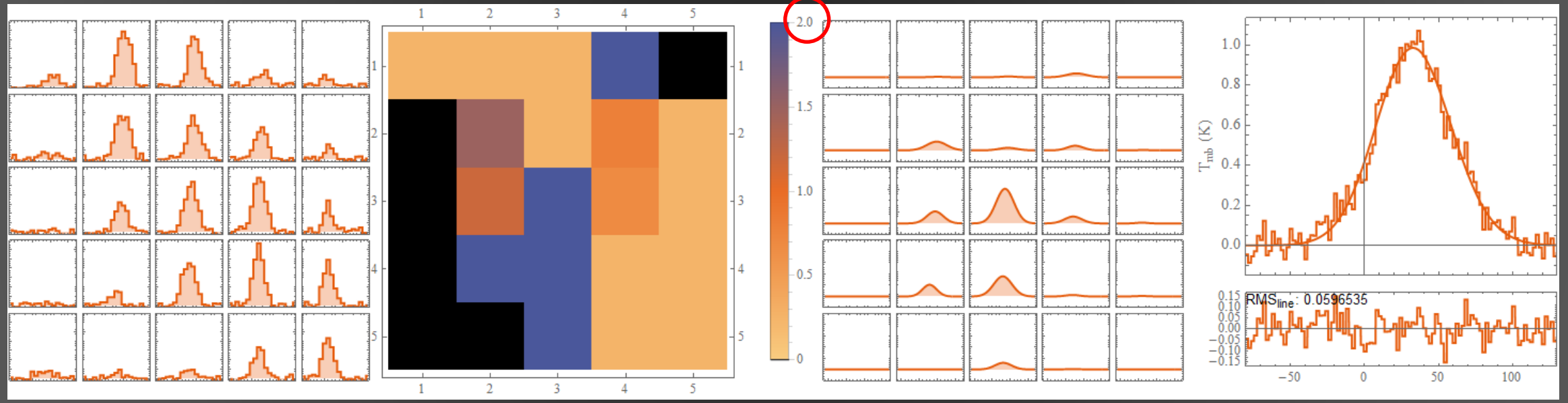



Convolve w. beam



# [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

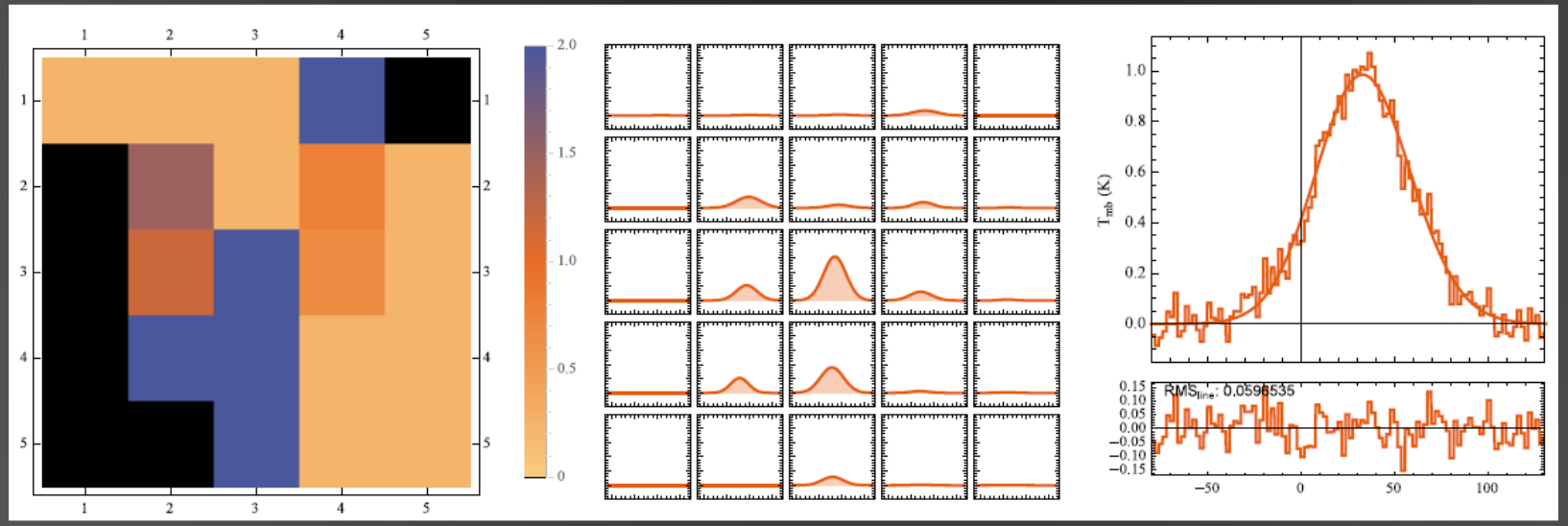
- Numerical fitting with 25(+1) degrees of freedom of varying weight is challenging
- The weaker the velocity gradient across the CO-map is, the higher the degeneracy between the parameters
  $\rightarrow$ kinematic influence of one CO position can be substituted by other positions with matching line 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

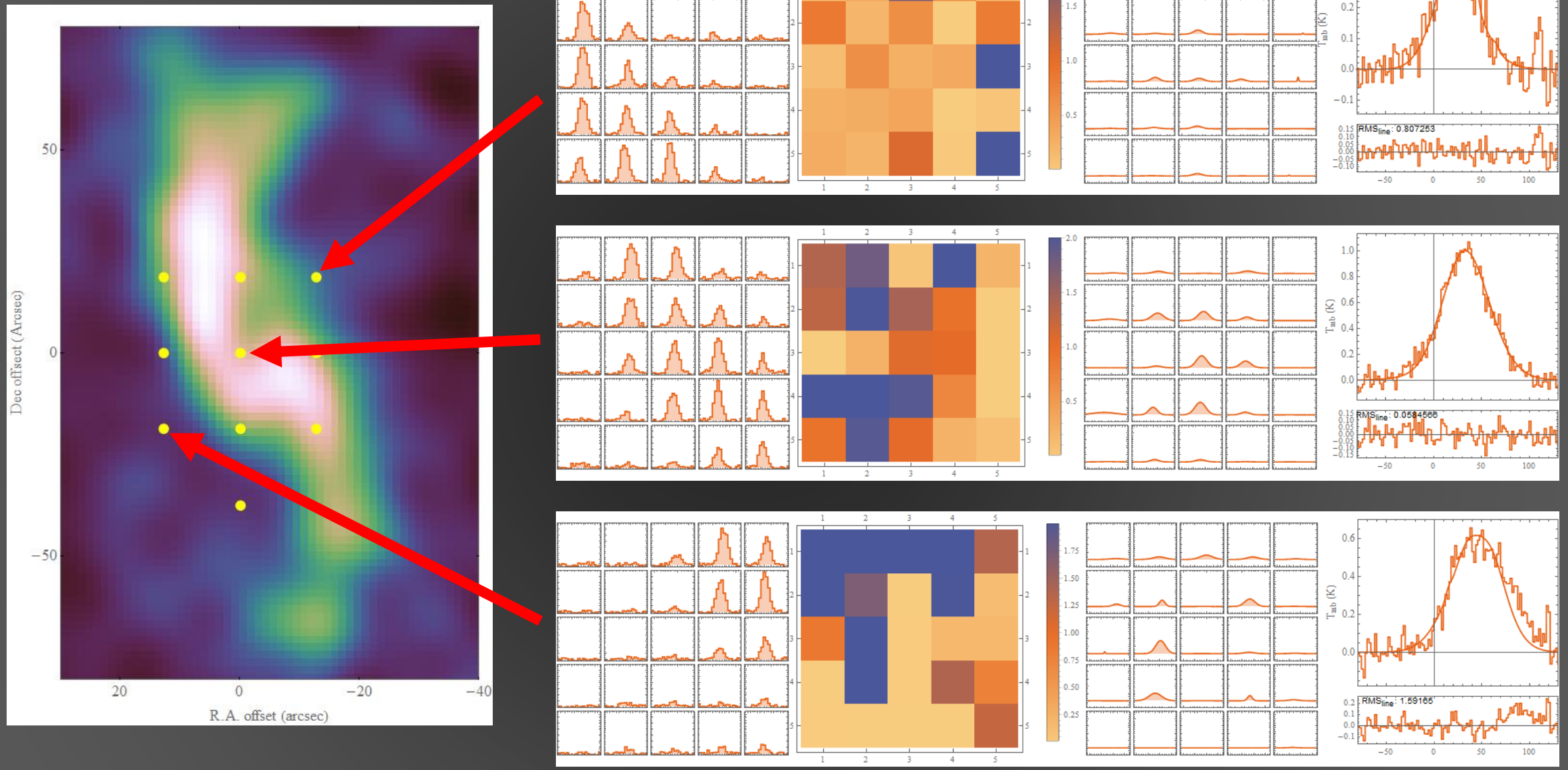
  $\rightarrow$ We find the same qualitative trends in the super-resolved [CII]/CO distribution with complementary methods

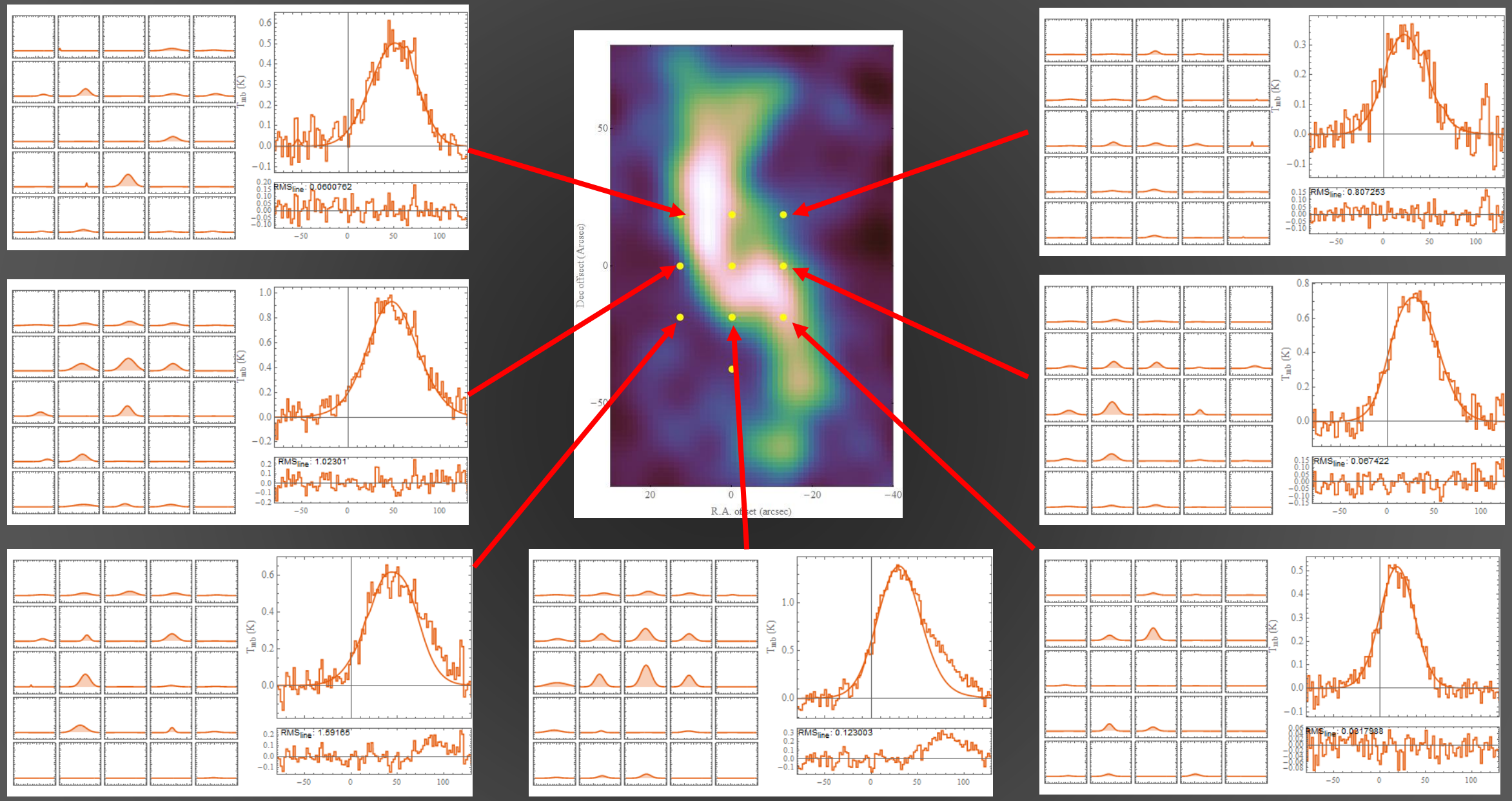
# [CII] Super-Resolution Composition

- 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.

(0,0) position




Dec offset (Arcsec)
R.A. offset (arcsec)
50
0
−50
20
0
−20
−40
$T_{mb}$ (K)
RMS$_{line}$: 0.807253
RMS$_{line}$: 0.0584668
RMS$_{line}$: 1.59165



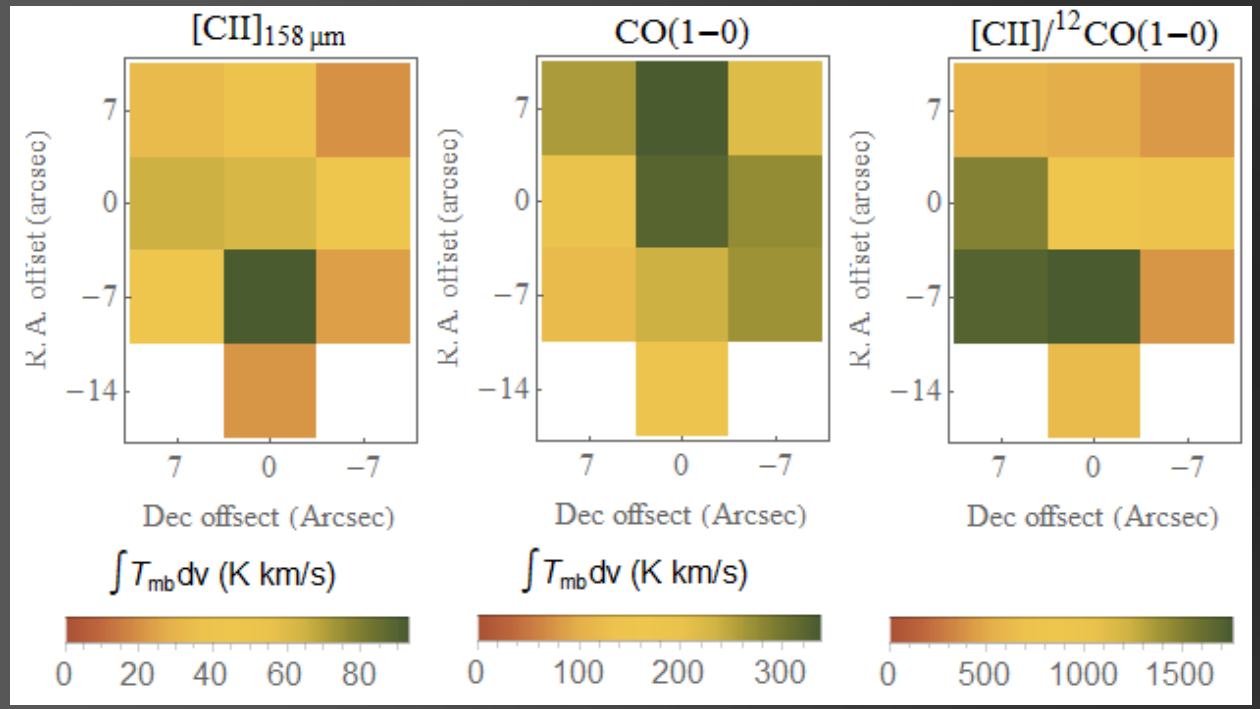

[CII] and [NII] emission in IC342 - The 6th Zermatt ISM Symposium - 7. Sep. 2015

# 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!

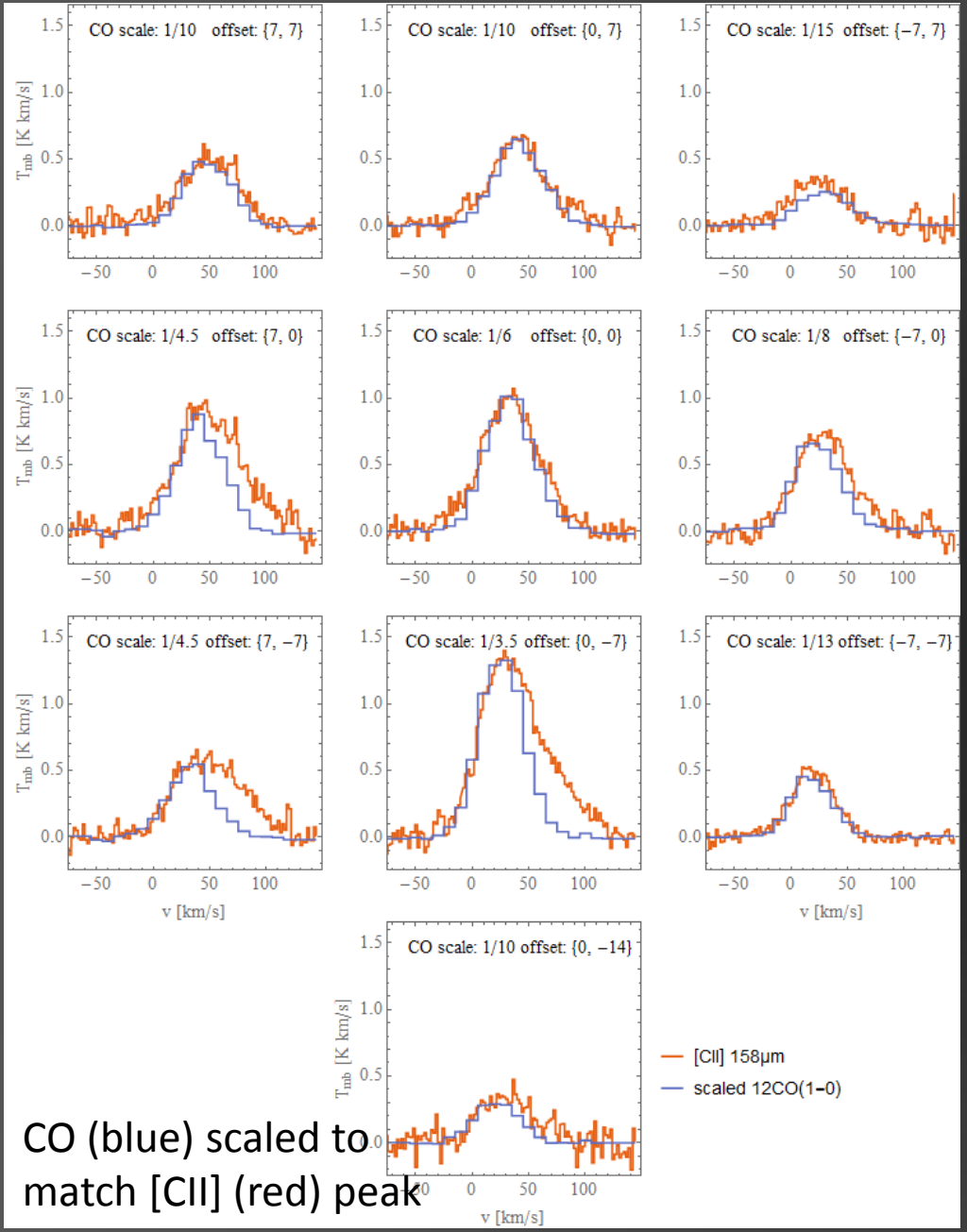
# [CII] to CO ratio



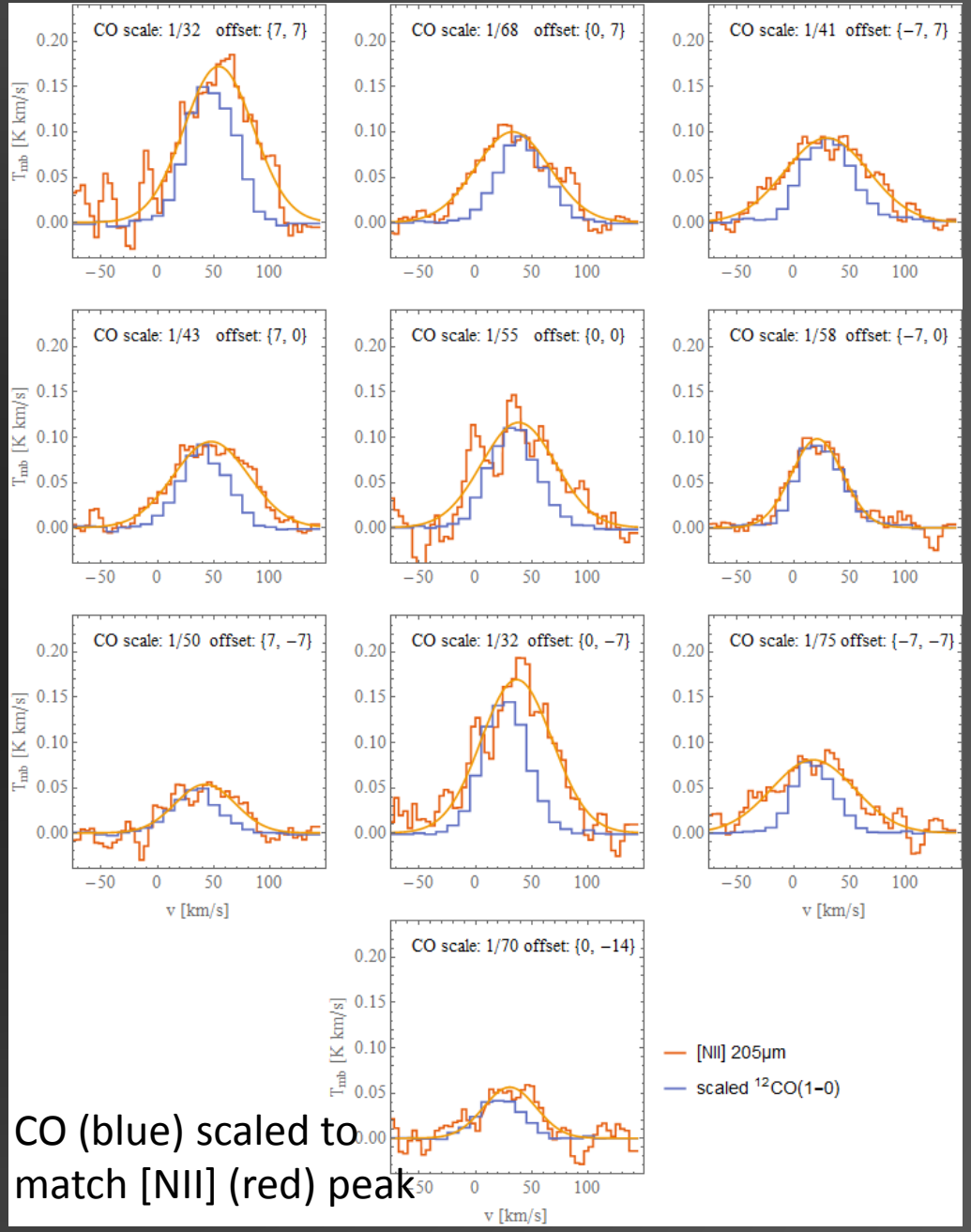

Röllig et al. 2015

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 activity along the molecular ring and mini-spiral.




CO (blue) scaled to match [CII] (red) peak



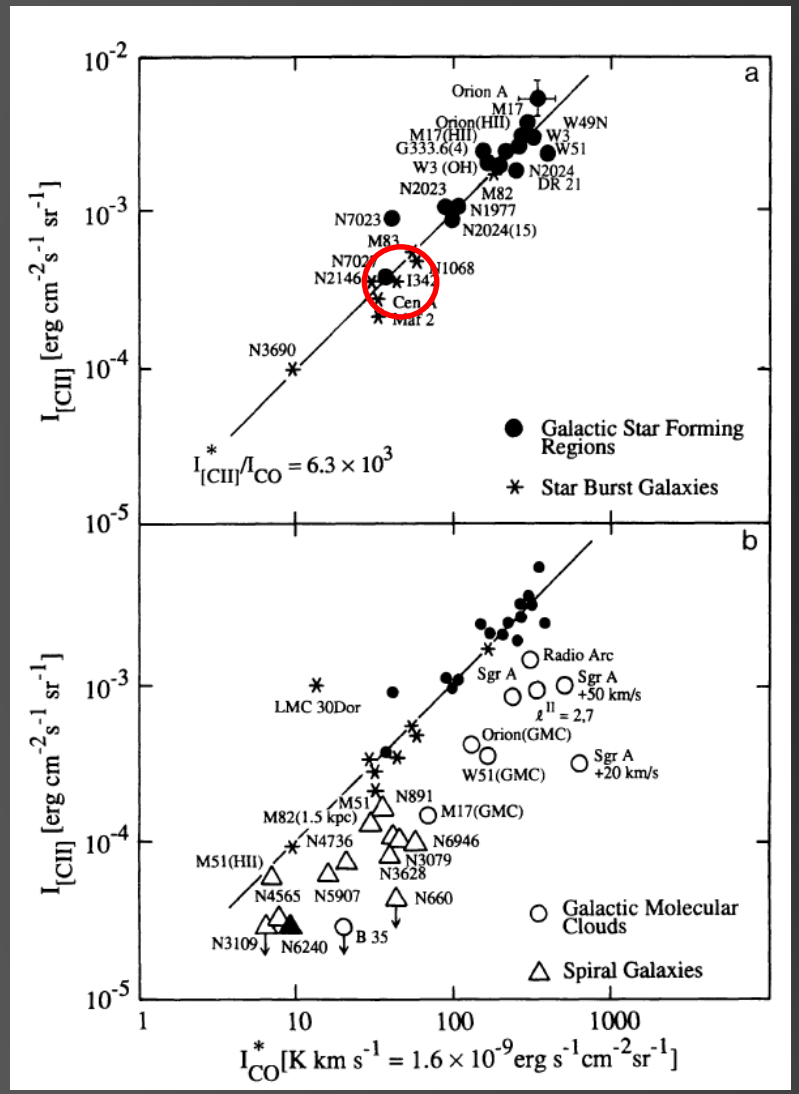

CO (blue) scaled to match [NII] (red) peak

# [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



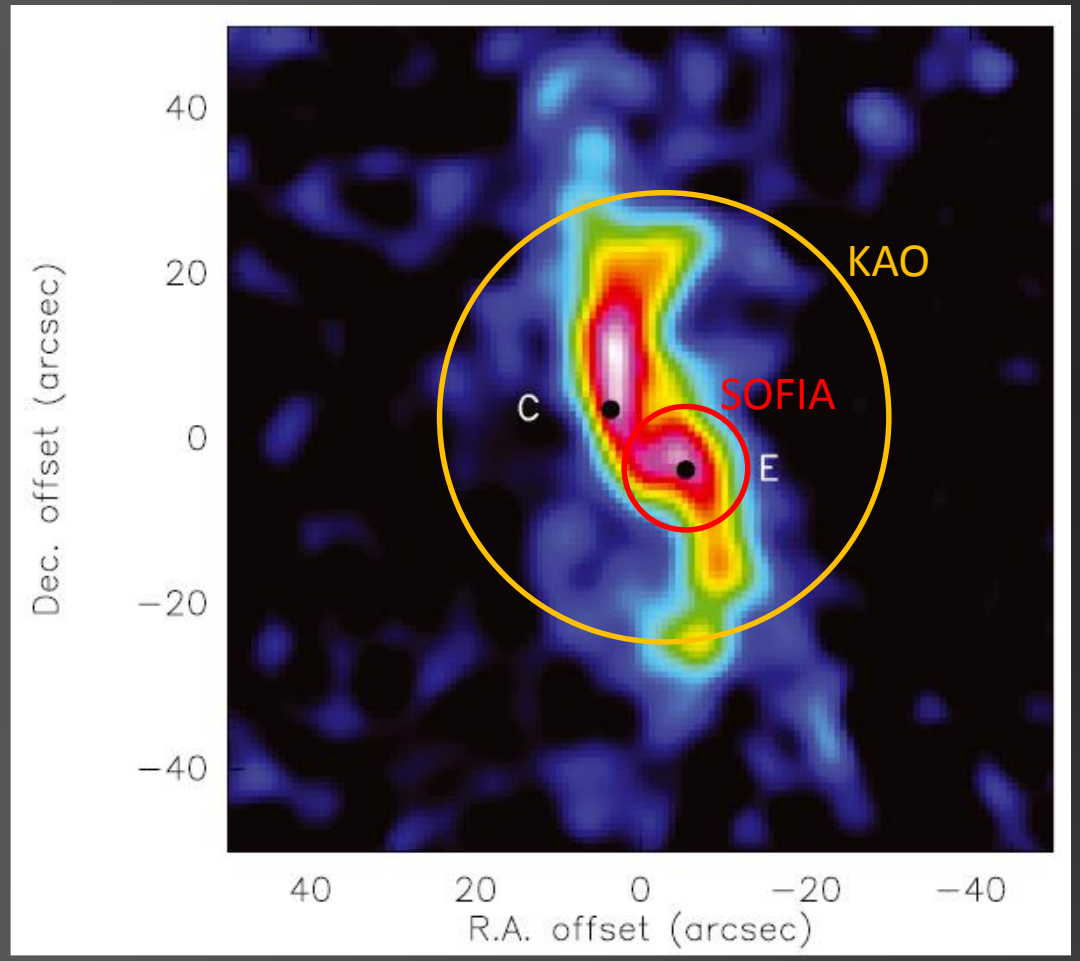

- $I_{[CII]}/I_{CO}$=4000-6000 is indicative of strong PDR activity/star bursts
- $I_{CO}$=37.7±1.8 K km/s @ 65“ beam (NRAO, Rickard & Blitz 1985)
- $I_{[CII]}$=3×10$^{-4}$ erg/s/cm$^2$/sr @ 55“ beam (KAO, Crawford et al. 1985)

**<u>Compare with higher resolution data</u>**

- $I_{CO}$=302 K km/s @ 15“ (BIMA, smoothed)
  $I_{[CII]}$=4.1×10$^{-4}$ erg/s/cm$^2$/sr @ 15“ (SOFIA)

Stacey et al. 1991

# KAO compared to SOFIA

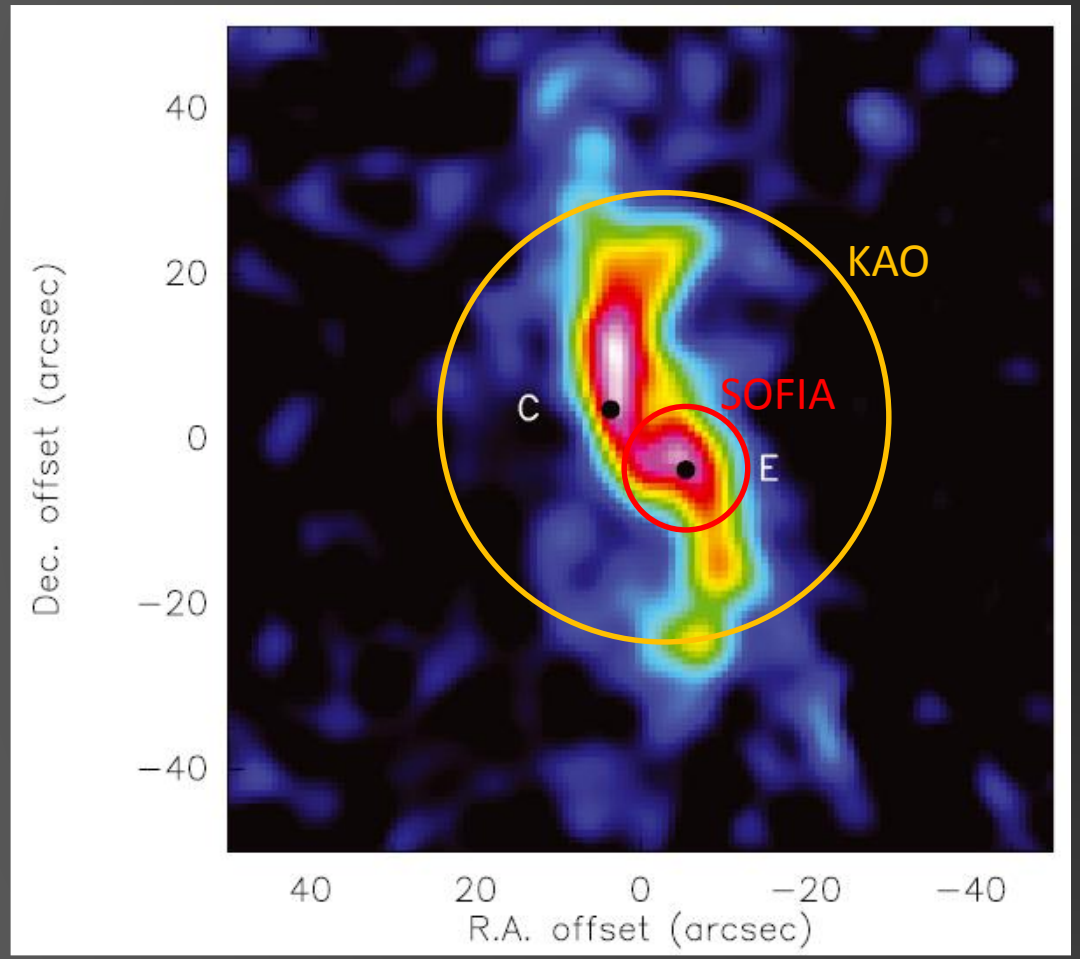



Stacey et al. 1991: [CII]/CO=5000

| | 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 |
| $M_{tot}$ [$10^6$ $M_\odot$] | 20 | 2.0/15 |
| $\chi$ [Draine] | 7 | 300/5 |

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

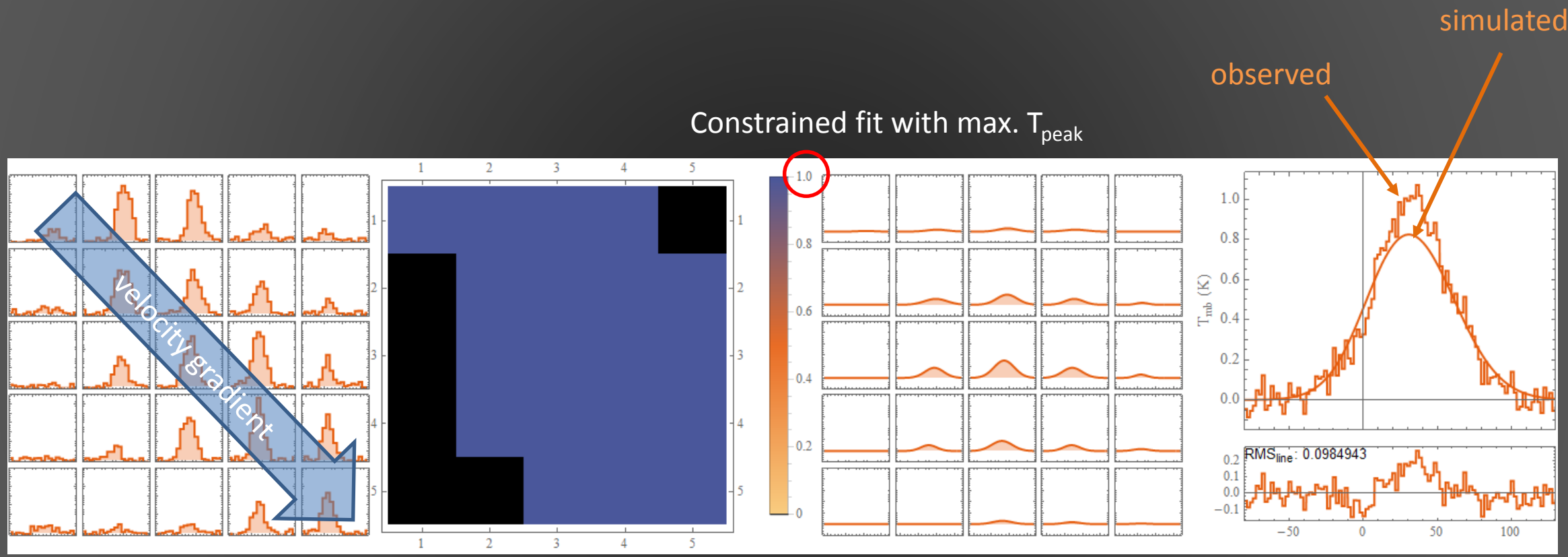
# KAO compared to SOFIA




- [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.

# [CII] Super-Resolution Composition



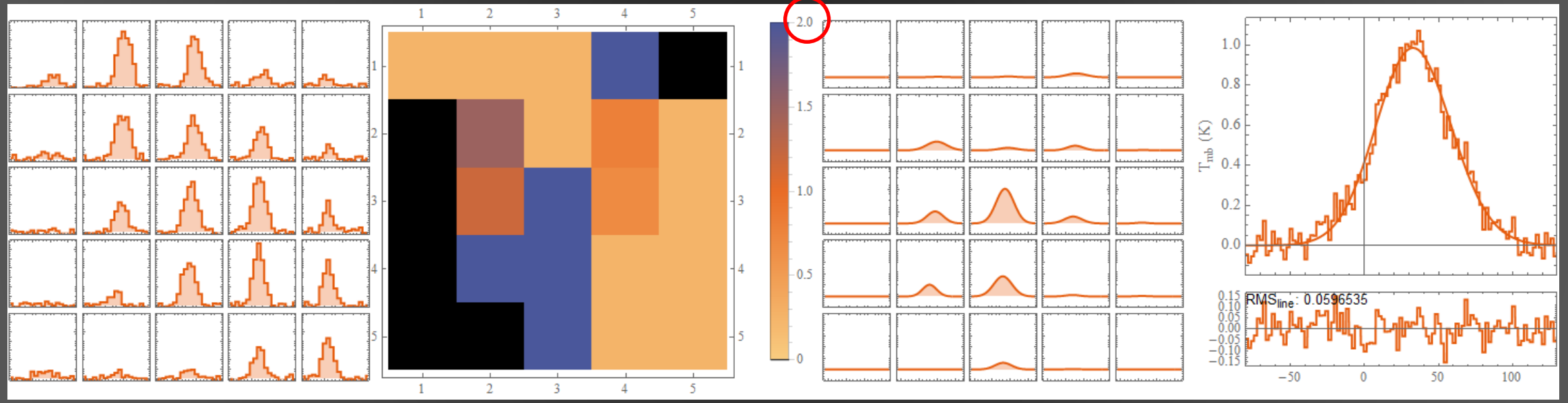

$T_{peak}$([CII]) @ each position

$[CII]^{hi\text{-}res}$ are already weighted with Gaussian kernel

residuum

# [CII] Super-Resolution Composition

Constrained fit with max. $T_{peak}$



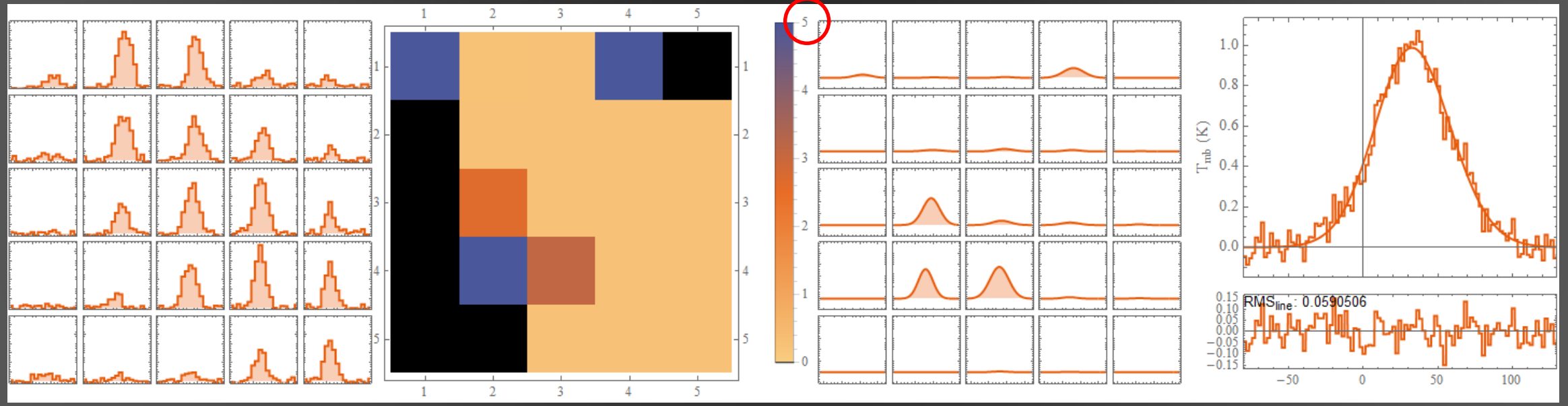

$T_{peak}$([CII]) @ each position

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

residuum

# [CII] Super-Resolution Composition

Constrained fit with max. $T_{peak}$

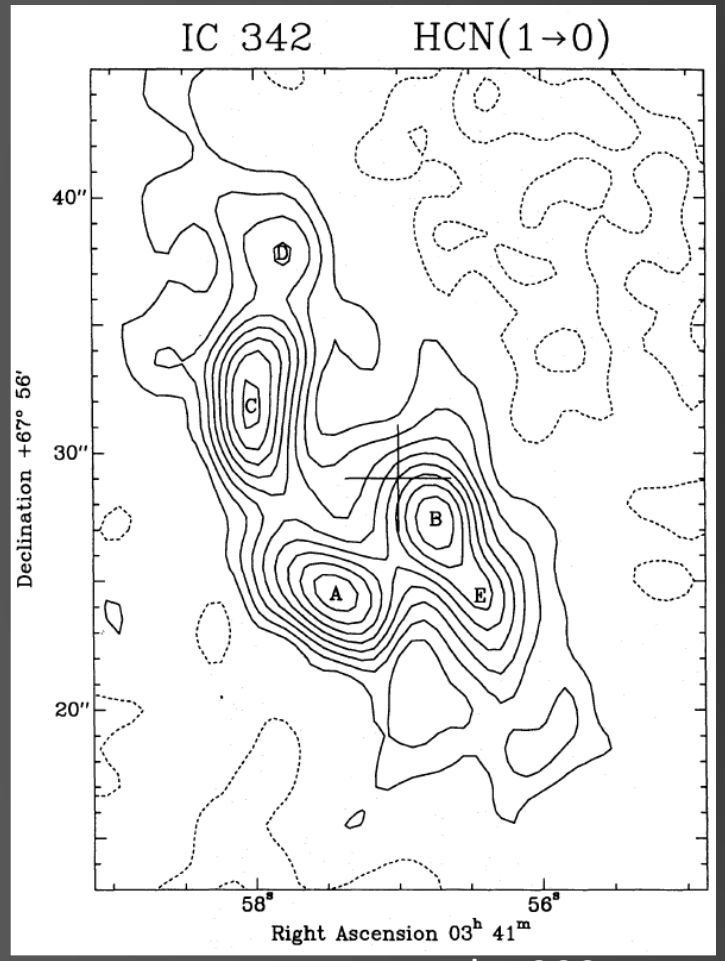



$T_{peak}$([CII]) @ each position

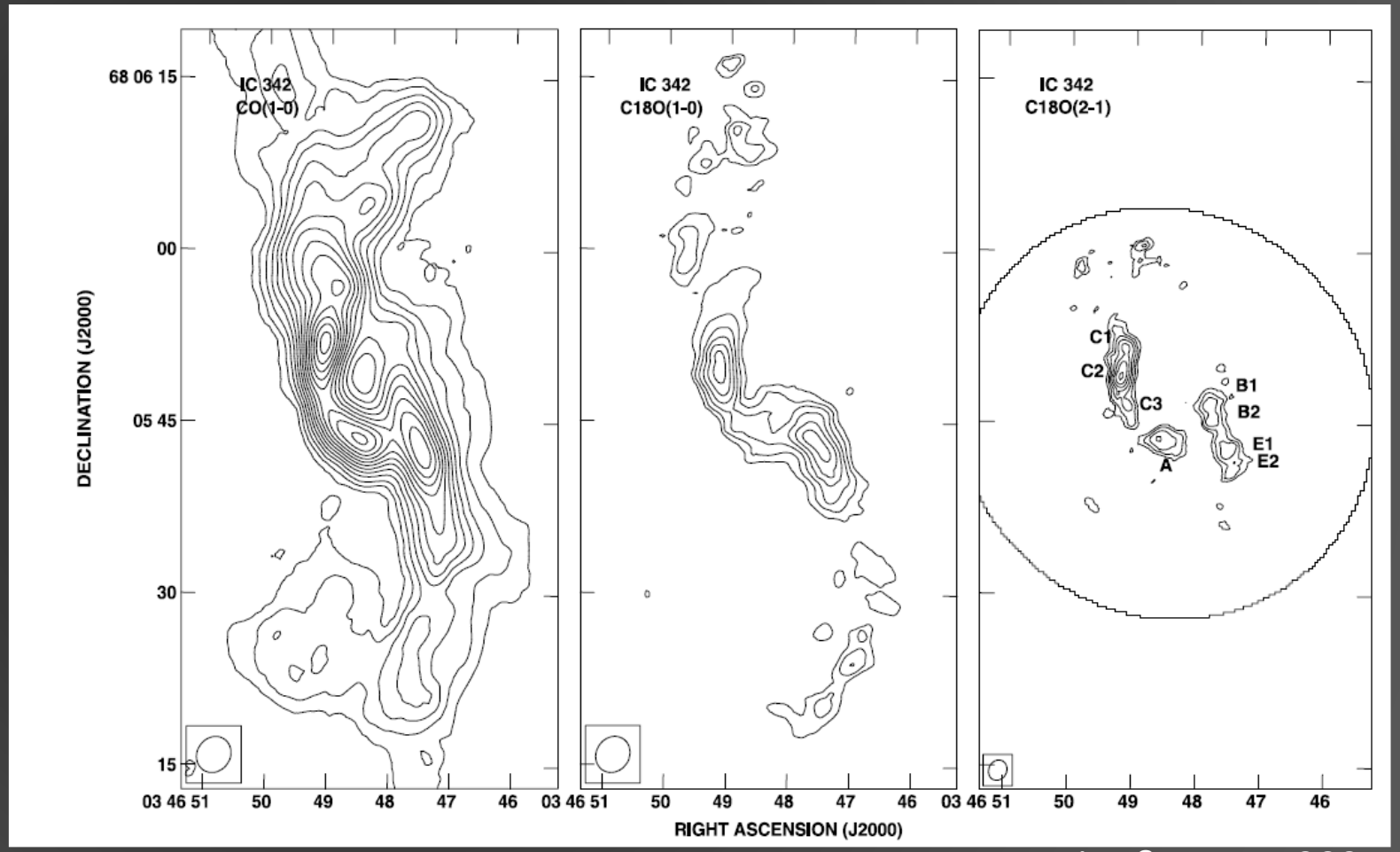
[CII]$^{hi}$ are already weighted with Gaussian kernel

residuum

# The Nucleus of IC 342




Downes et al. 1992




Meier & Turner 2001