Excitation and Energetics of the Dense gas in M17 SW

A synergy of SOFIA/GREAT, APEX & IRAM 30m observations

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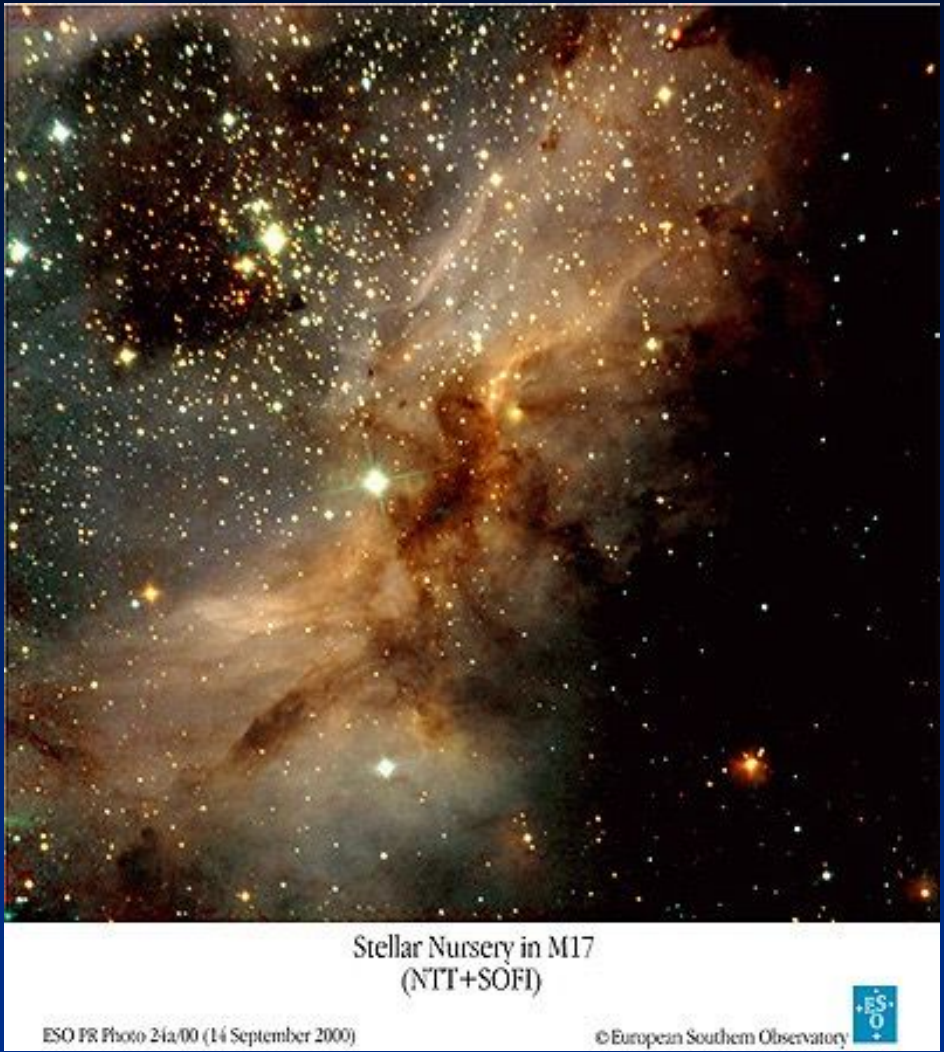
V. Ossenkopf, J. Stutzki, et al. (2)

M. Spaans (3)

MPIfR (1) - II.Phys. Inst. Uni. Köln (2) - Kapteyn Astronomical Institute (3)

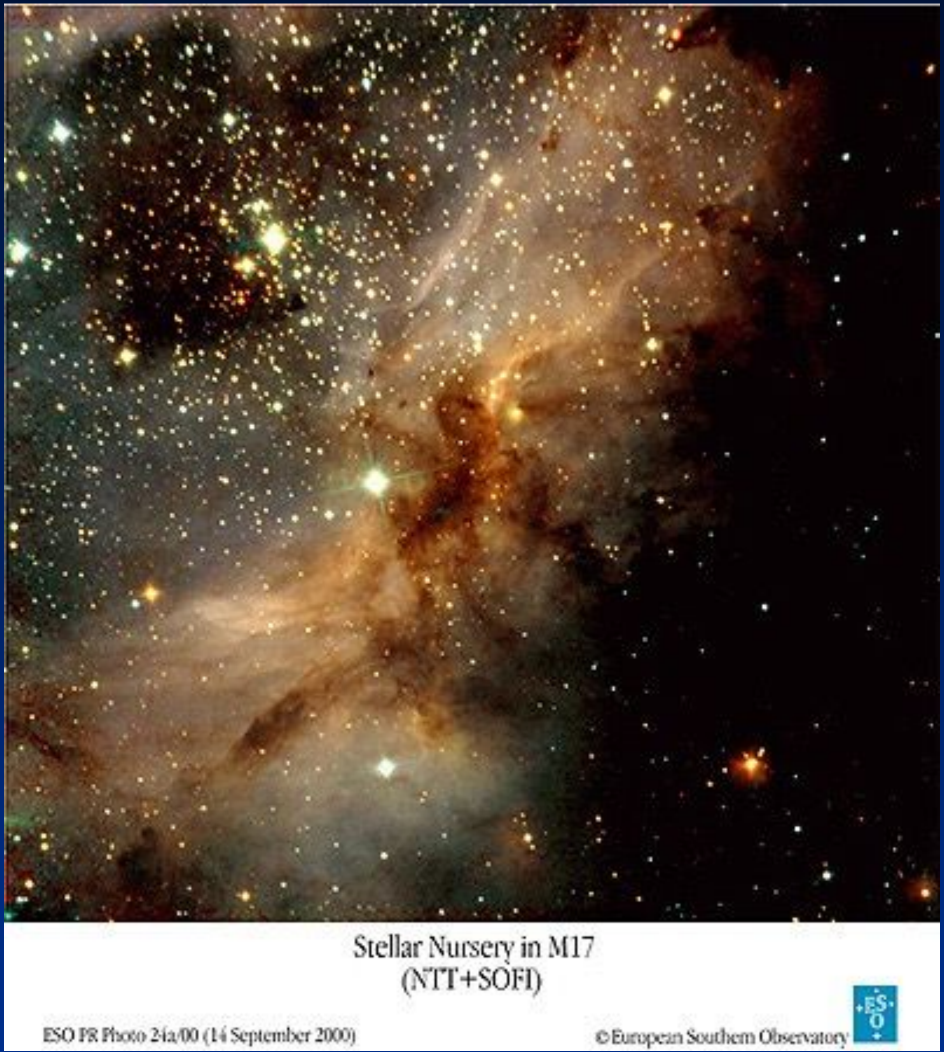
SOFIA Community Tele-Talk **November 4th, 2015**

M17 SW

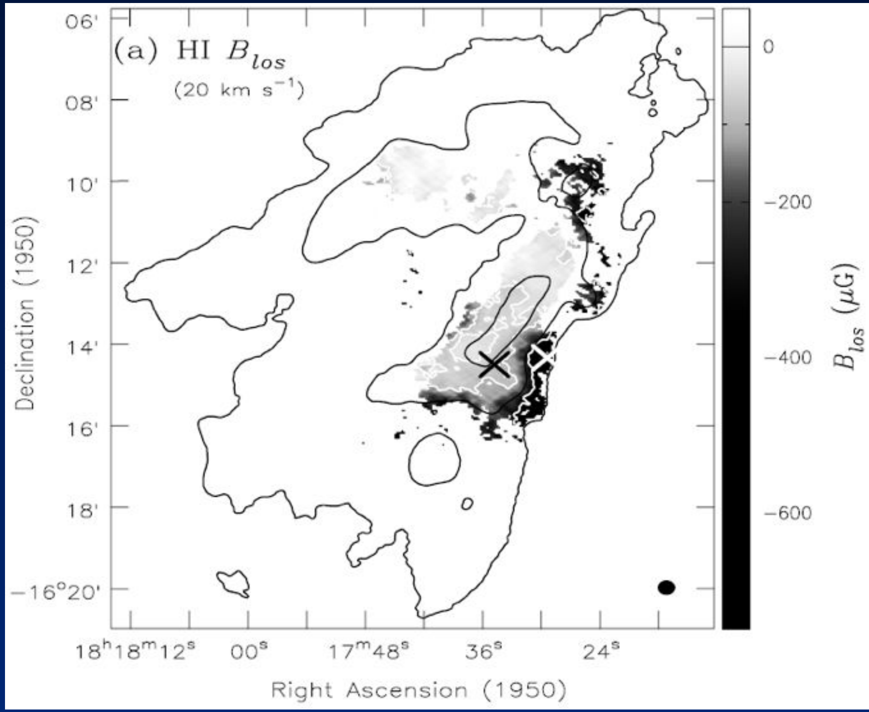


- M17 SW, the Omega or Swan Nebula (in Sagittarius constellation) is one of the most massive and dense molecular cloud cores of the Galaxy.
- Illuminated by UV radiation from young, massive stars ~ 6 times hotter and 30 times more massive than the Sun.
- $n(H_2)$ ~ 10^4 - 10^6 cm^{-3} and T_K ~ 50 – 300 K
- **Mass: ~ 1.5x10^4 M_{sun} (Stutzki & Güsten 1990)**
- Gas dominated by magnetic pressure rather than thermal pressure (Pellegrini et al. 2007)
- Geometry: nearly edge on
- **Distance~1.98 kpc (Xu et al. 2011) → 1''~0.009 pc**
- **Location: 18h20m27s -16°12'00'' (J2000.0)**
- **Image size ~ 5x5 arcminutes**

M17 SW



H I Zeeman observations B_{los}



Gas dominated by magnetic pressure rather than thermal pressure (Brogan & Trolland 2001, Pellegrini et al. 2007)

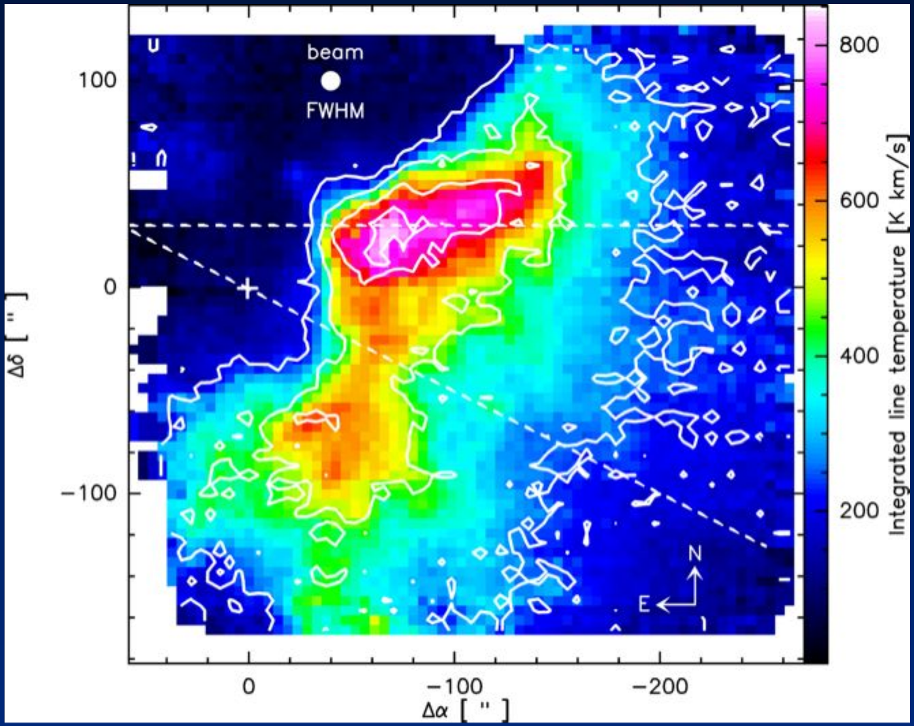
- **The ~1 Myr old OB open cluster**

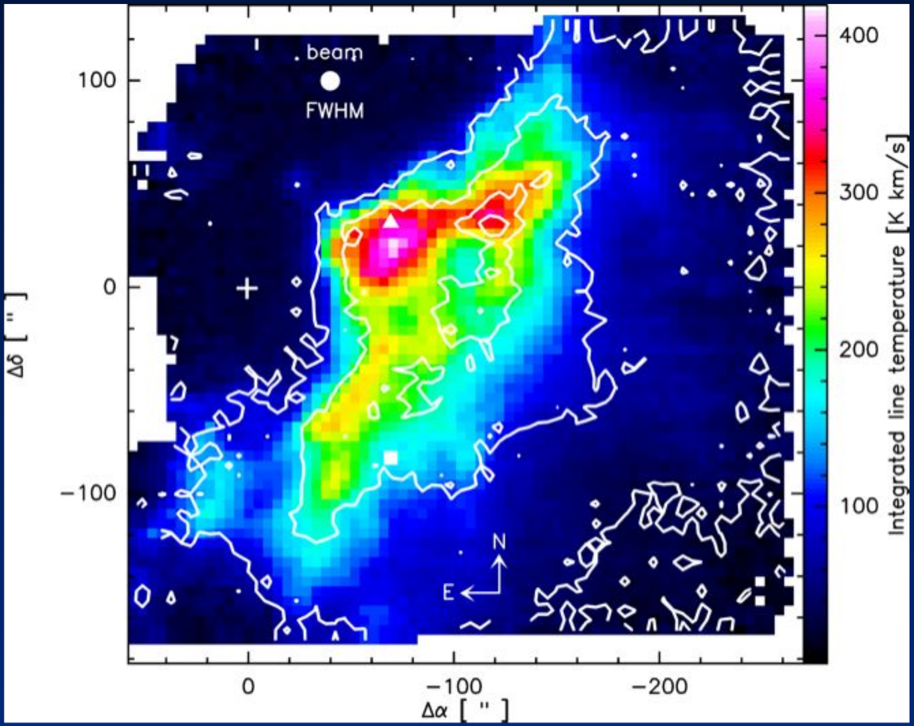
No signs of shocks!

APEX/CHAMP$^+$ previous results

CO *J*=6-5 color map

^{13}CO *J*=6-5 color map





CO *J*=7-6 contour map

[C I] 370 µm contour map

FWHM (661 GHz) ~ 9.4'' (~0.08 pc)

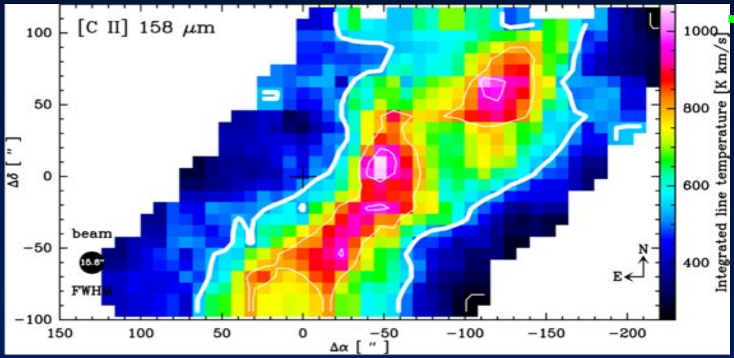
Map size ~ 3x3 pc^2

Pérez-Beaupuits et al. (2010) - *A&A, 510, A87*

SOFIA/GREAT previous results

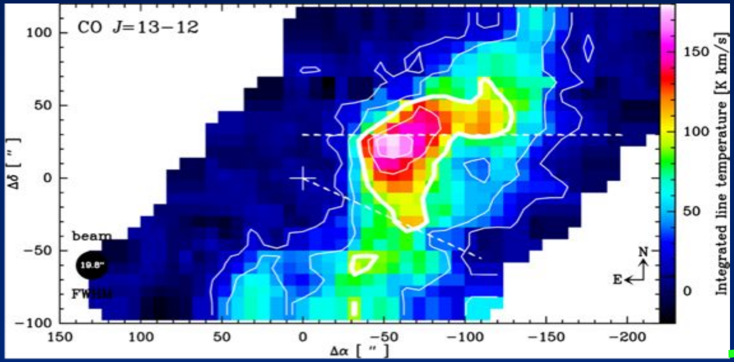
[C II] @ 1.9 THz

- FWHM ~ 15.6"
- Sampling step = 8"
- Pixel size = -4" x 4"



^{12}CO J=13-12 @ 1.4 THz

- FWHM ~ 19.8"
- Sampling step = 8"
- Pixel size = -4" x 4"

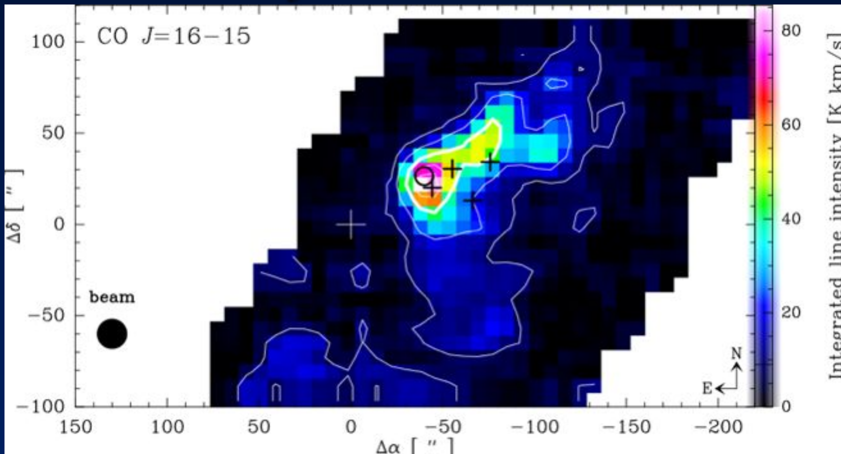


Pérez-Beaupuits et al. (2012)

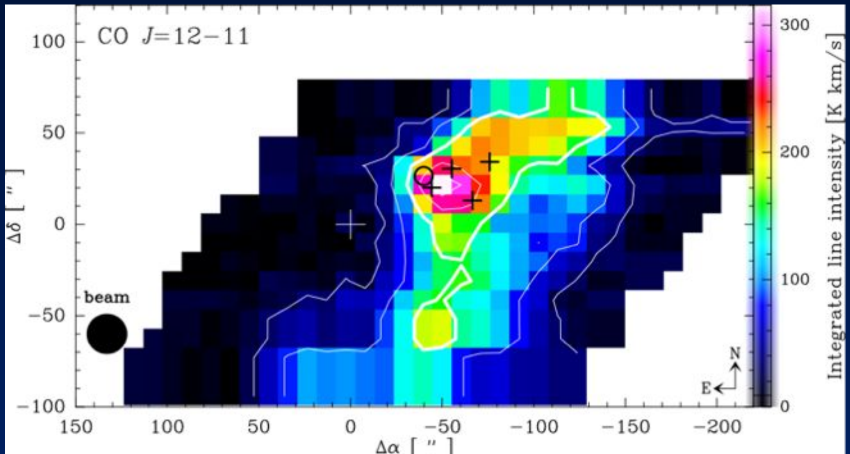
A&A, 542, L13

SOFIA/GREAT new results

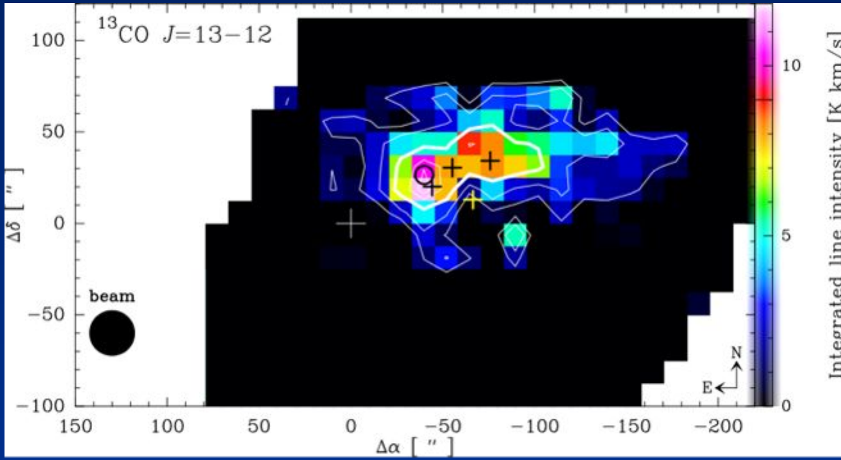
^{12}CO *J*=16-15 @ 1.84 THz



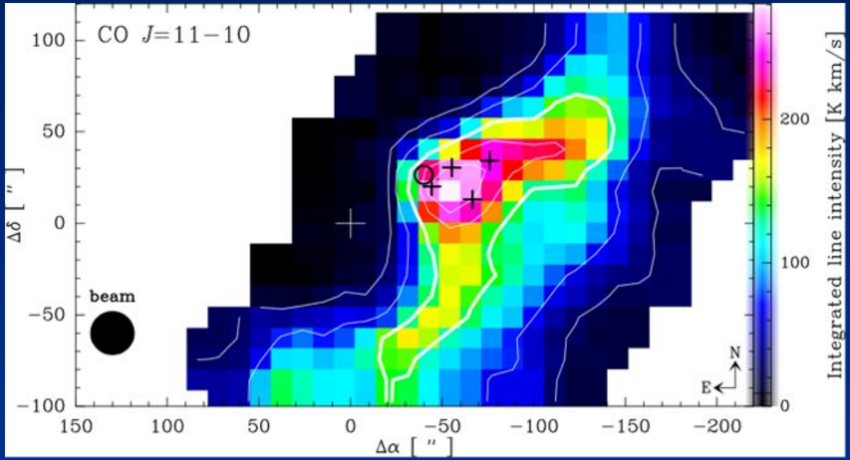
^{12}CO *J*=12-11 @ 1.38 THz



^{13}CO *J*=13-12 @ 1.43 THz



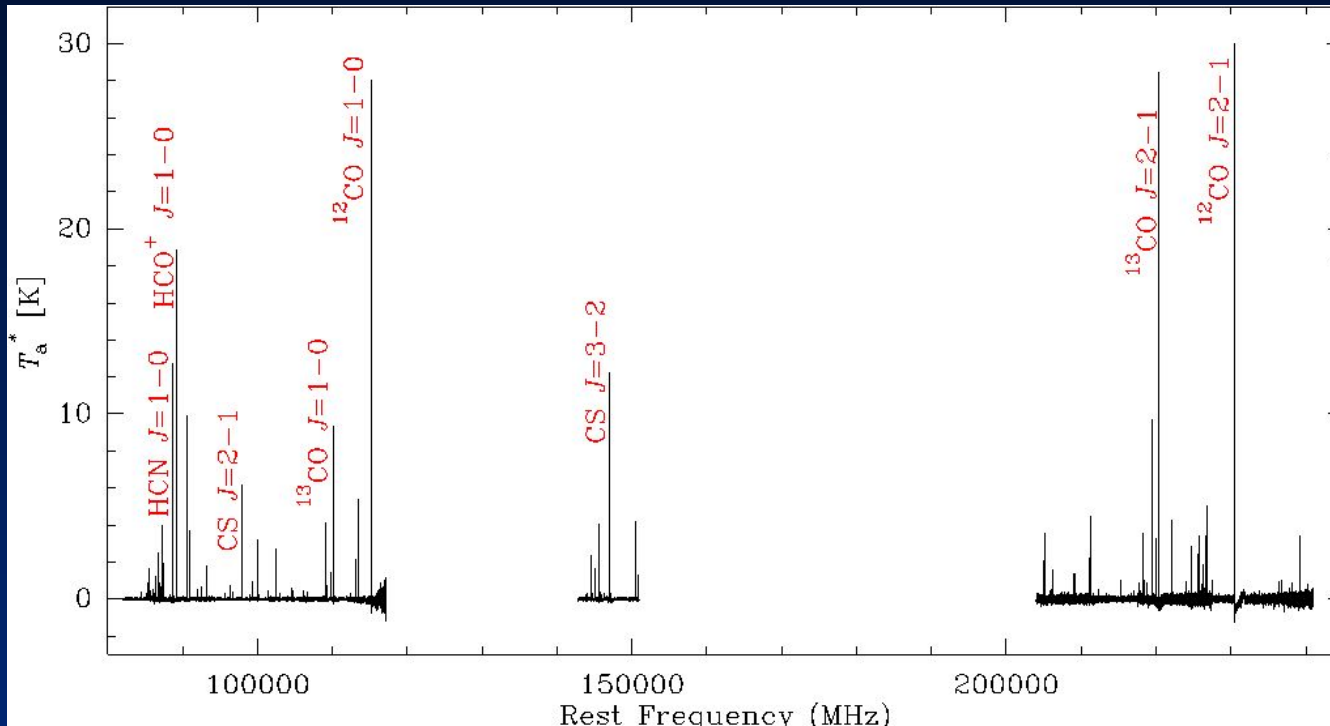
^{12}CO *J*=11-10 @ 1.26 THz



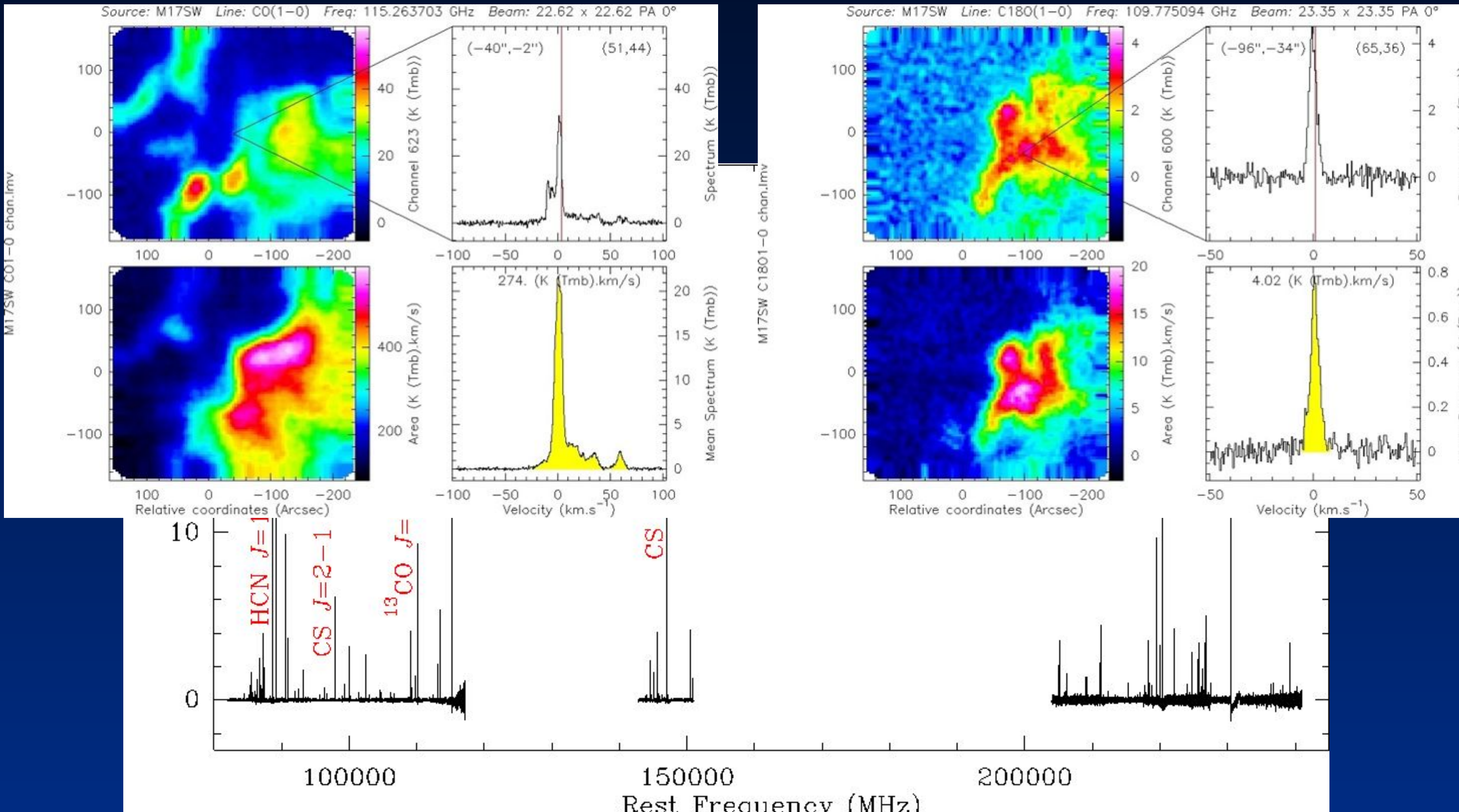
Pérez-Beaupuits et al. (2015) A&A, 583, A107

New IRAM 30m/EMIR OTF Survey

3mm 2mm 1mm



New IRAM 30m/EMIR OTF Survey



Pérez-Beaupuits et al. (2015), A&A, 575, A9

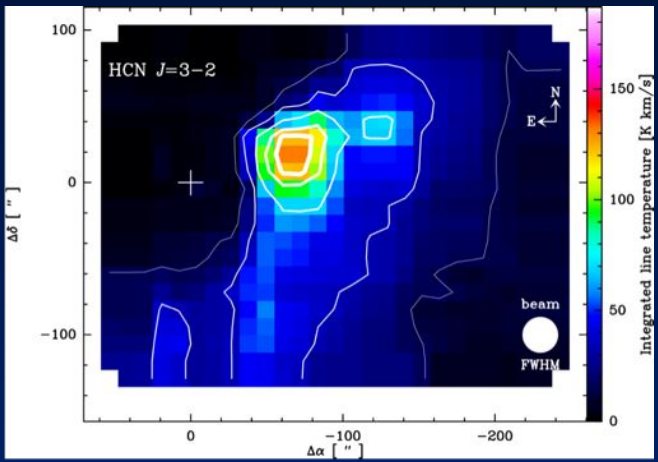
Full maps ~2.8 x 3.6 pc^2

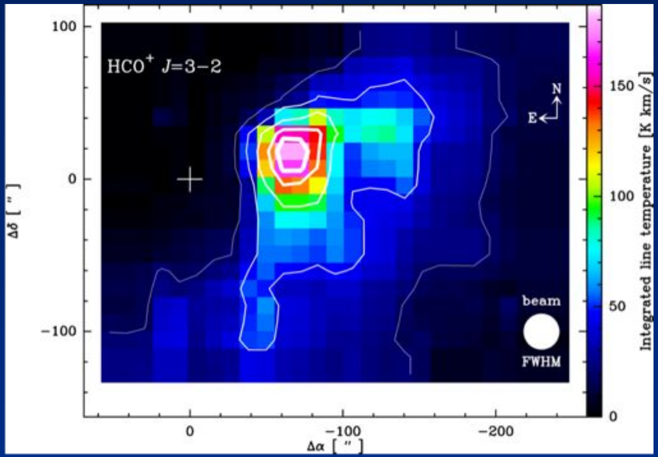
^{12}CO, ^{13}CO *J*=1-0, *J*=2-1

HCN, H^{13}CN, HCO$^+$, H^{13}CO$^+$ *J*=1-0

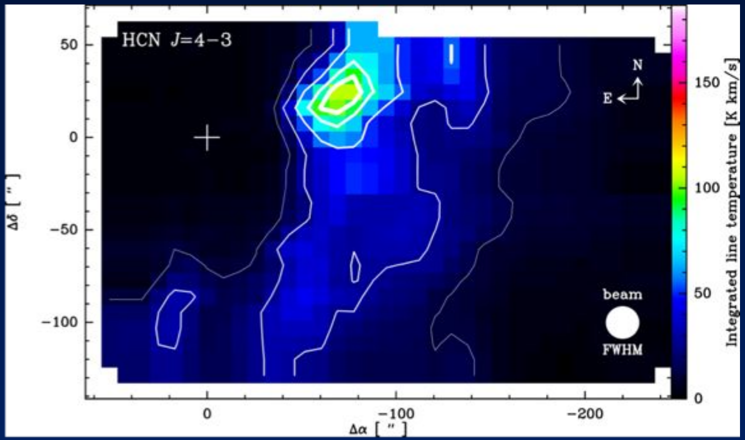
New APEX/FLASH & A2 results

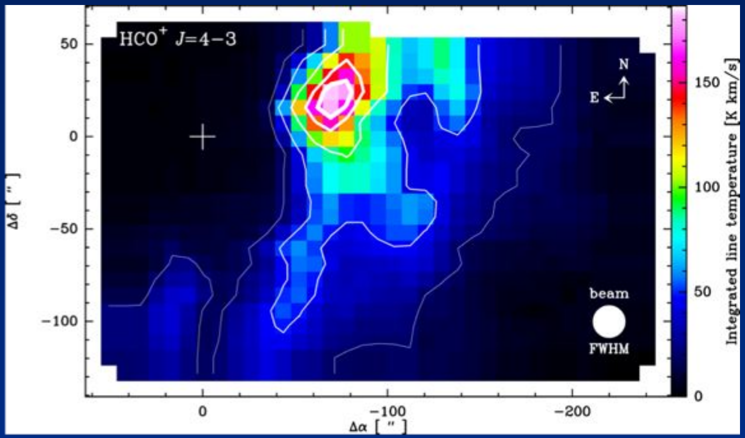
HCN & HCO^+ J=3-2





HCN & HCO^+ J=4-3



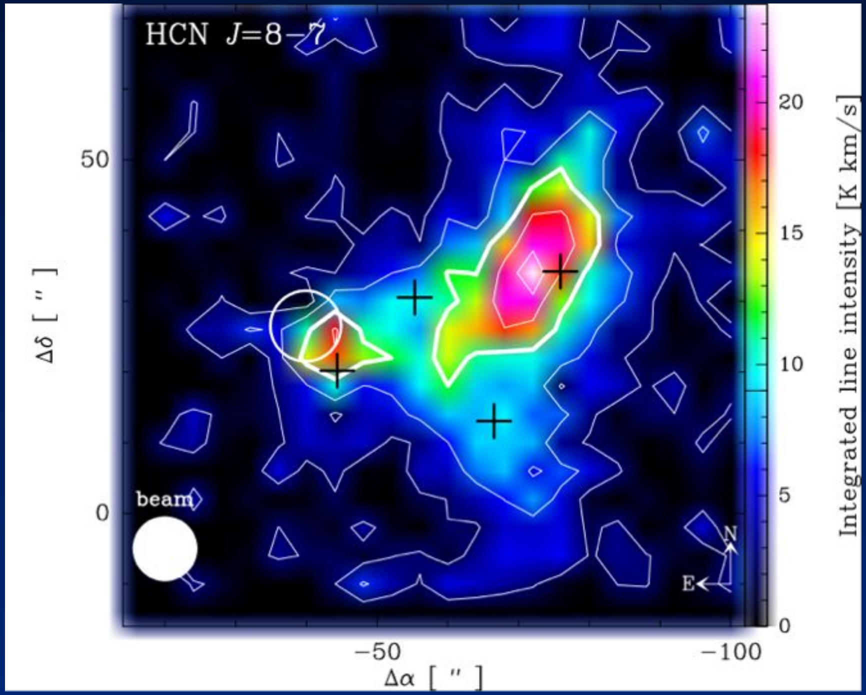


also $H^{13}CN$ J=3-2, J=4-3 & $H^{13}CO^+$ J=3-2

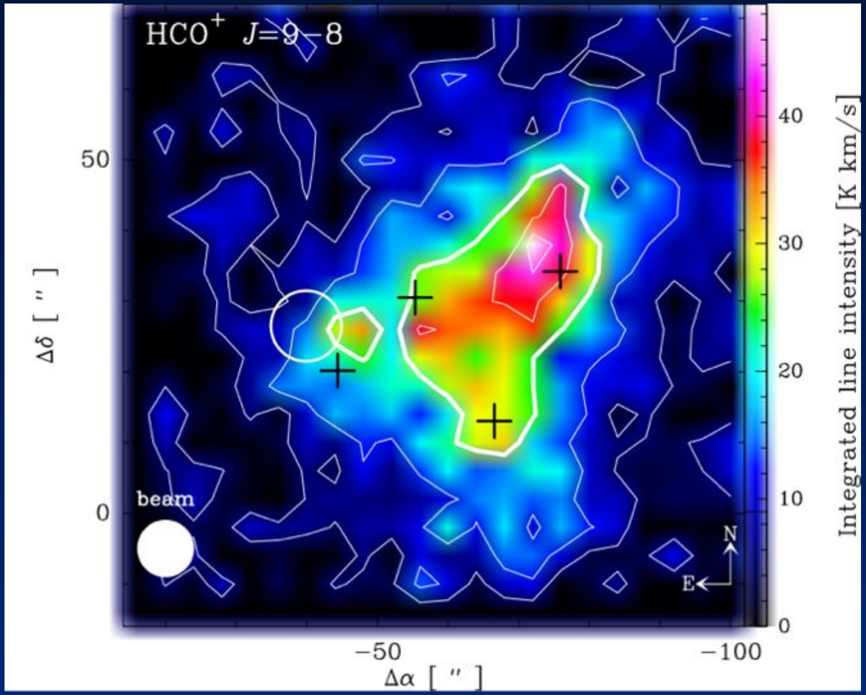
Pérez-Beaupuits et al. (2015) A&A, 583, A107

New APEX/CHAMP+ results

HCN *J*=8-7 @ 708.8 GHz



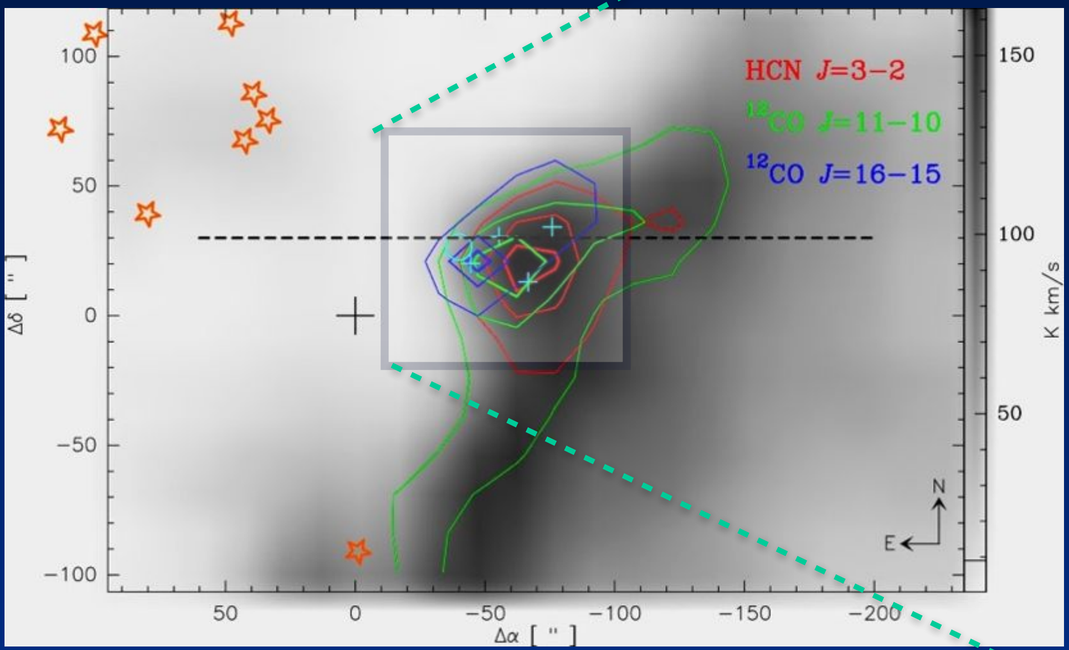
HCO^+ *J*=9-8 @ 802.5 GHz

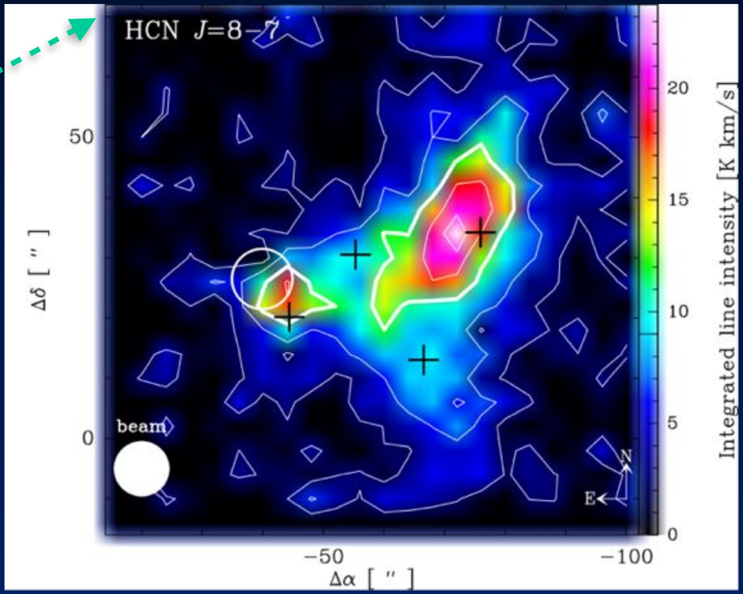


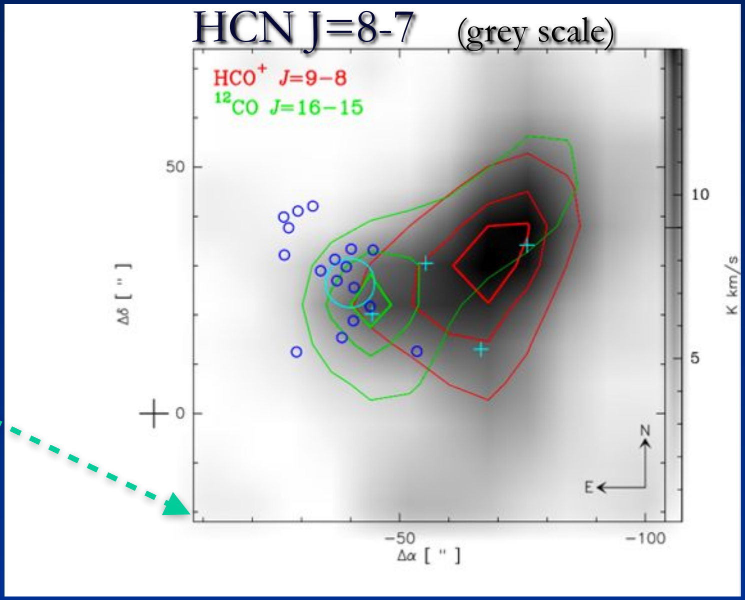
Pérez-Beaupuits et al. (2015) A&A, 583, A107

Context of the Excitation Conditions

HCN J=1-0 (grey scale)





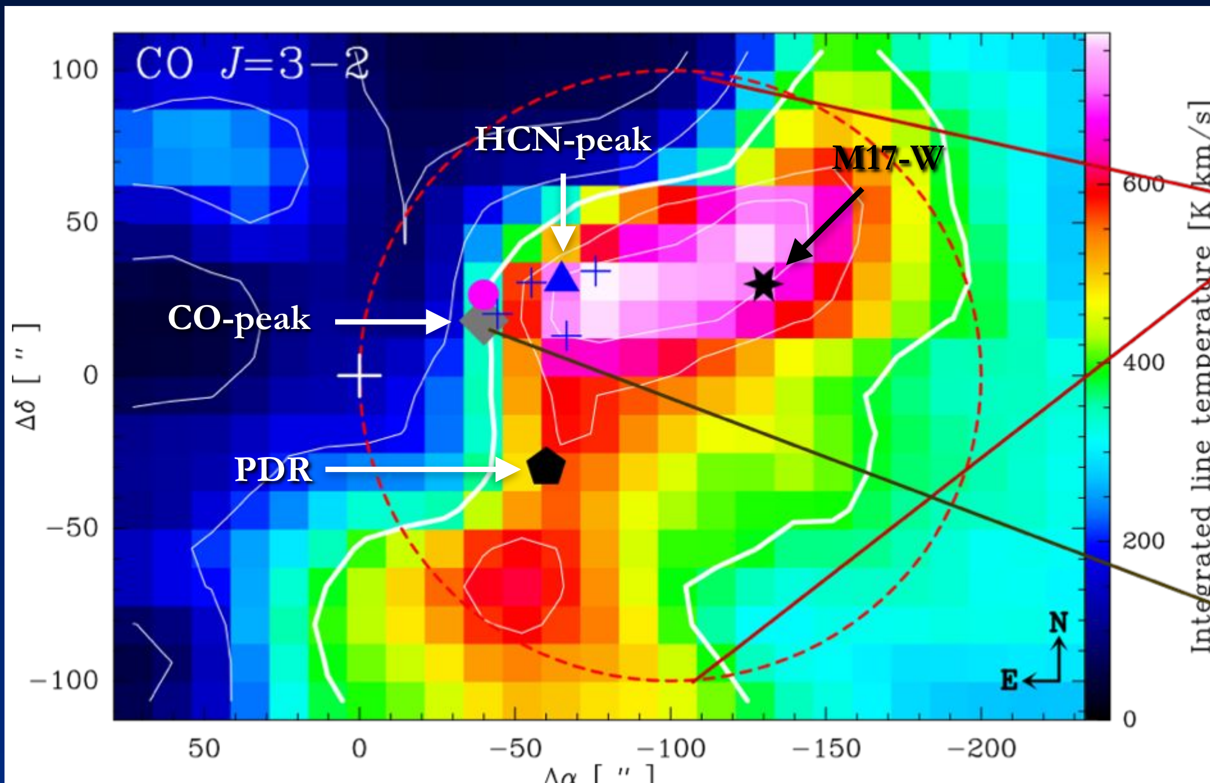


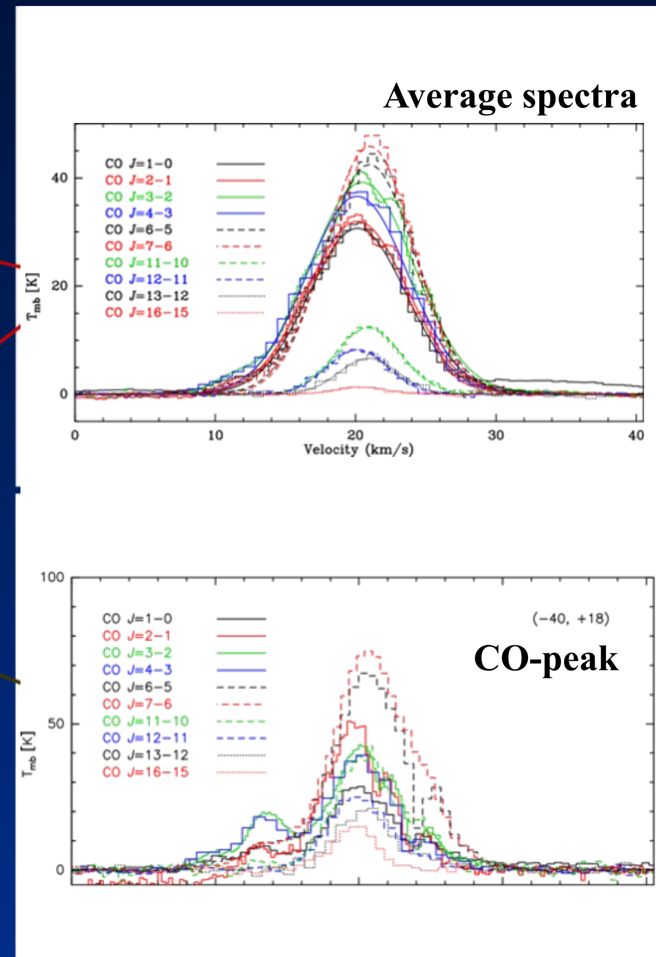
crosses: H_2O masers (Johnson et al. 1998)
blue circles: X-ray sources (Broos et al. 2007)

Pérez-Beaupuits et al. (2015) A&A, 583, A107

Beam Dilution Effects

Spectra from a 200” (2 pc) diameter region

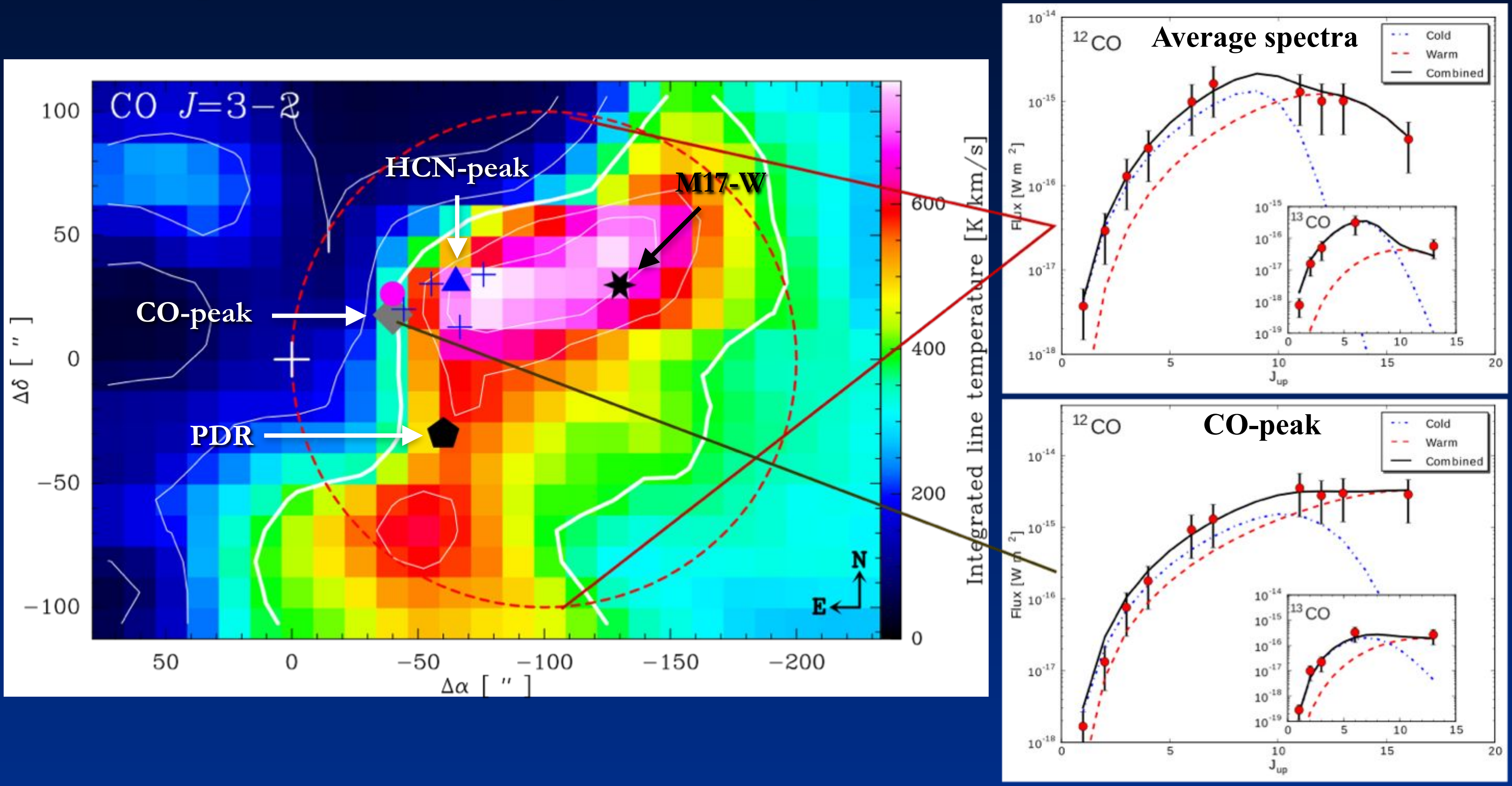




Pérez-Beaupuits et al. (2015) A&A, 583, A107

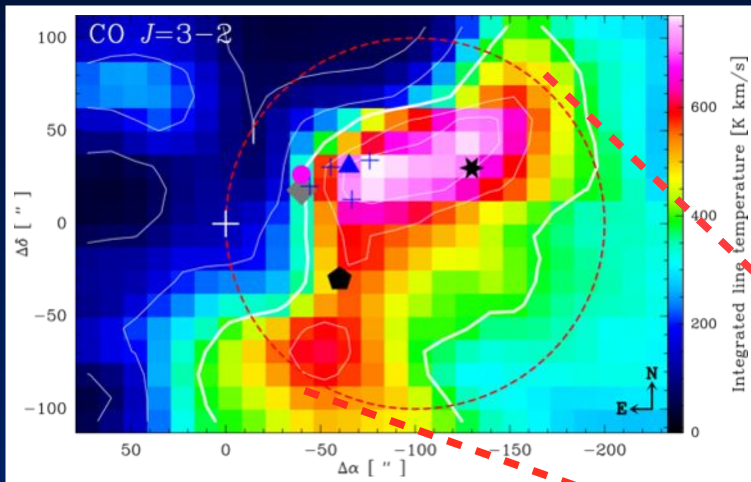
Beam Dilution Effects

Spectra from a 200" (2 pc) diameter region

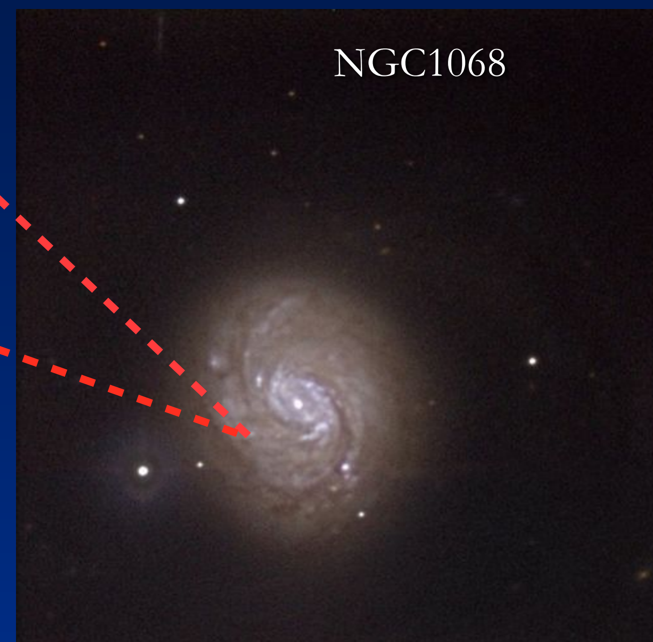


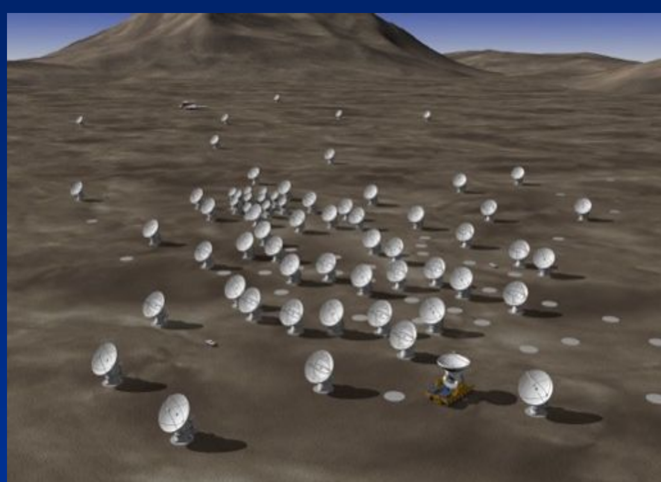
Pérez-Beaupuits et al. (2015) A&A, 583, A107

Extragalactic connection - ALMA



Molecular clouds of ~2 pc diameter can be resolved by ALMA with the current finest angular resolution of 0.03" (Cycle 3) in nearby galaxies like NGC 1068 ~14 Mpc (z ~ 0.0038)





Radiative Transfer Model

Line intensities (from RADEX)

$$F_{tot}(v) = \Phi_{cold} F_{cold} + \Phi_{warm} F_{warm}$$

Filling factors [0,1]

RADEX: van der Tak et al. (2007)

$F_i = F_i(n_i, T_i, N_i, dv)$ *8 free parameters*

i = *cold, warm*

ϕ_i = filling factor
$n_i = n_i(H_2)$ [cm^{-3}]
T_i = kinetic temperature [K]
N_i = column density [cm^{-2}]
dv = velocity line width [km/s]

From Gaussian fit

Constraints of the parameters

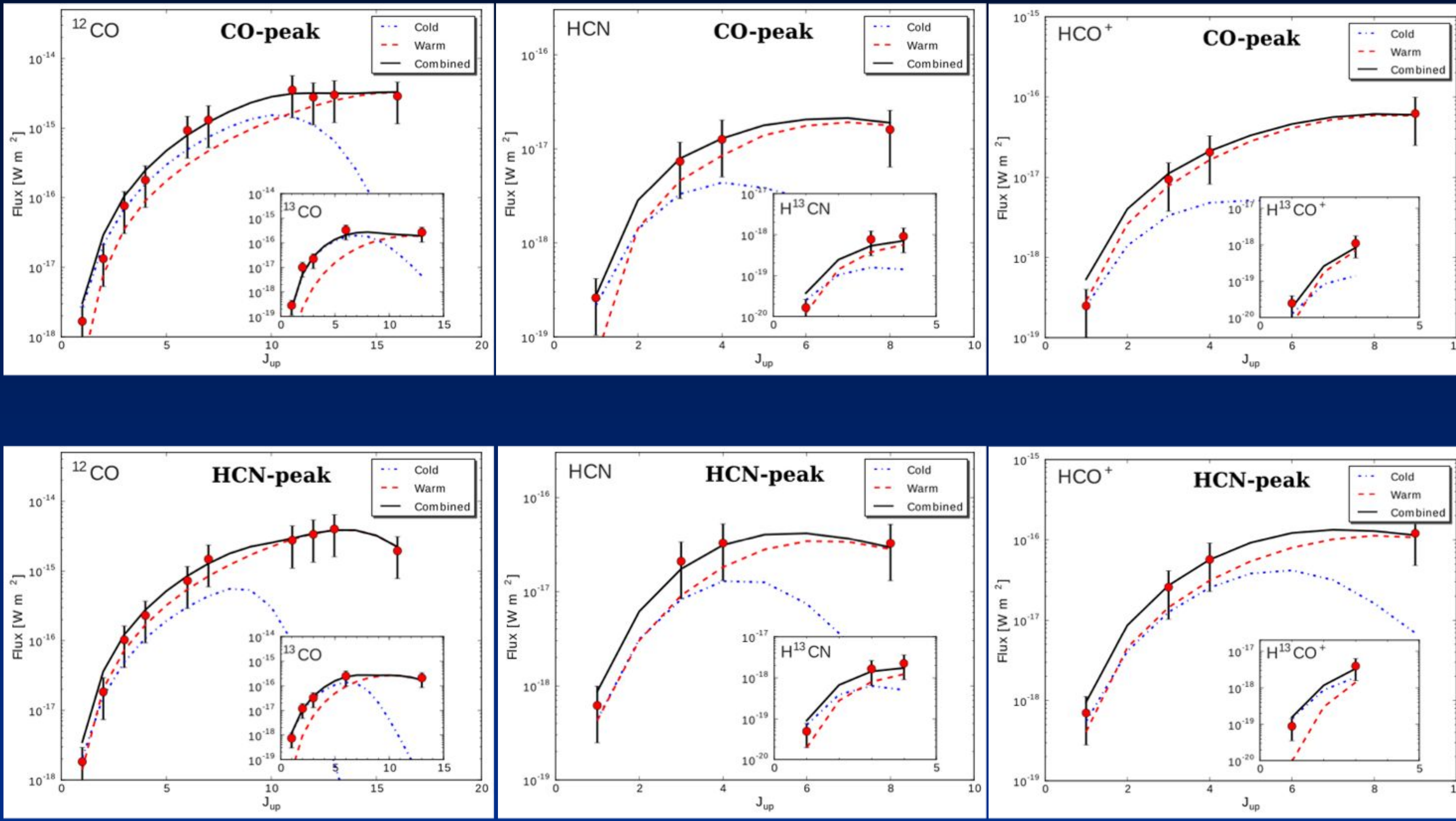
$\phi_i(^{13}C) = \phi_i(^{12}C)$

$\phi_{warm} < \phi_{cold} \leq 1$

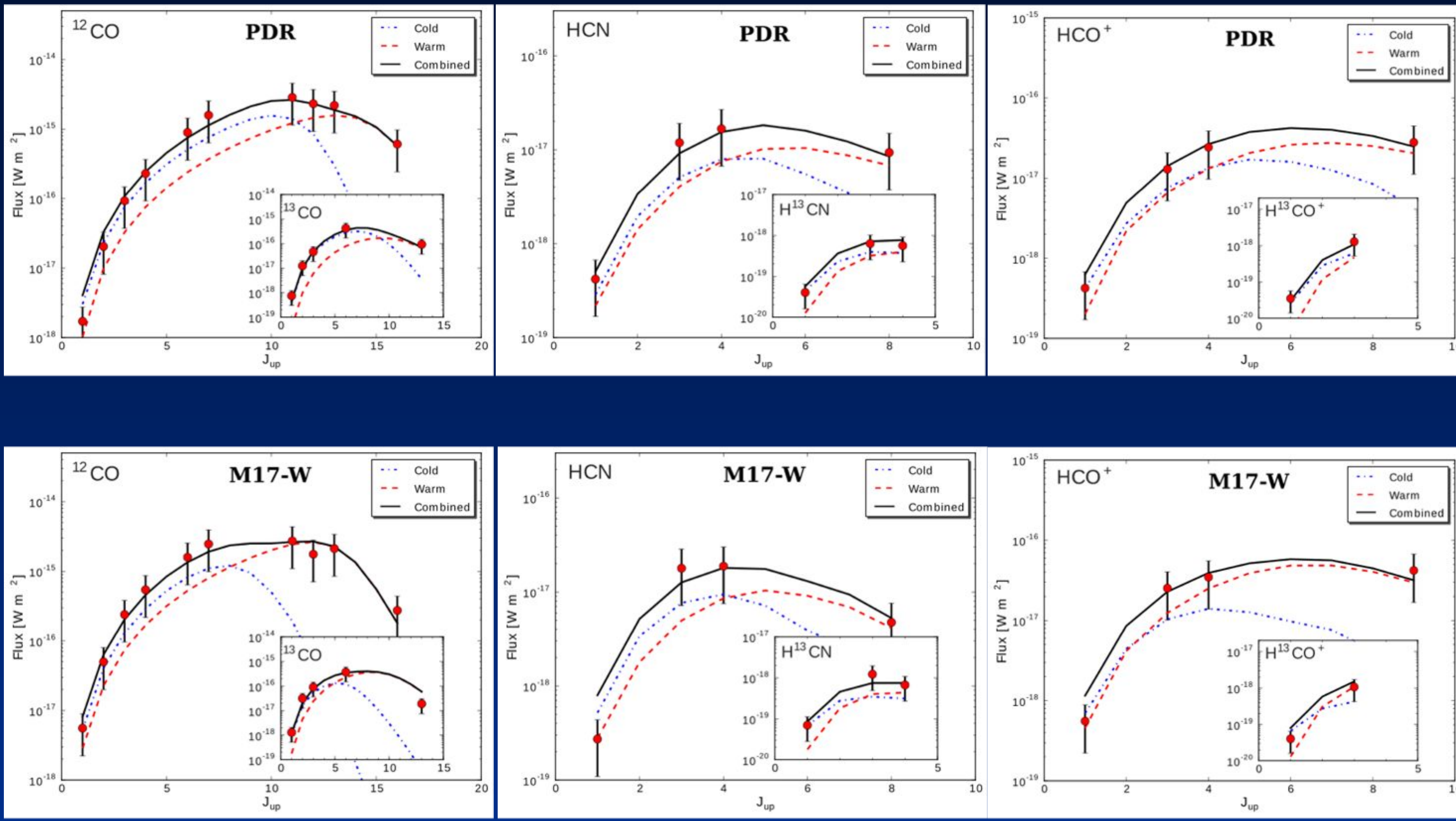
Same n_i and T_i for CO, HCN, HCO^+ and isotopologues

$N_i(^{13}C) = N_i(^{12}C)/\mathcal{R}_{12/13}$ $\mathcal{R}_{12/13} = [^{12}CO]/[^{13}CO] = 50$

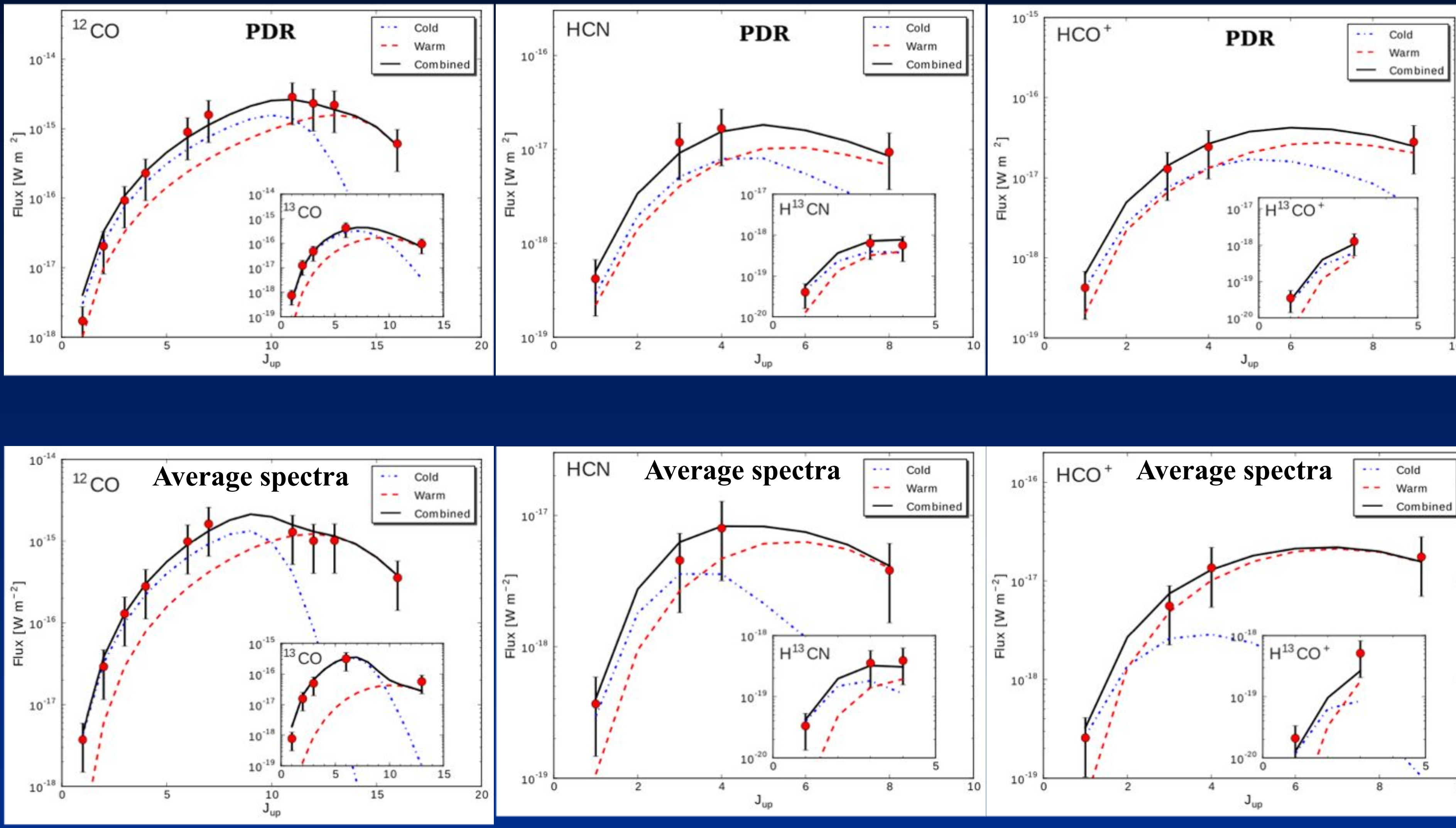
Line Spectral Energy Distributions (LSEDs) - I



Line Spectral Energy Distributions (LSEDs) - II

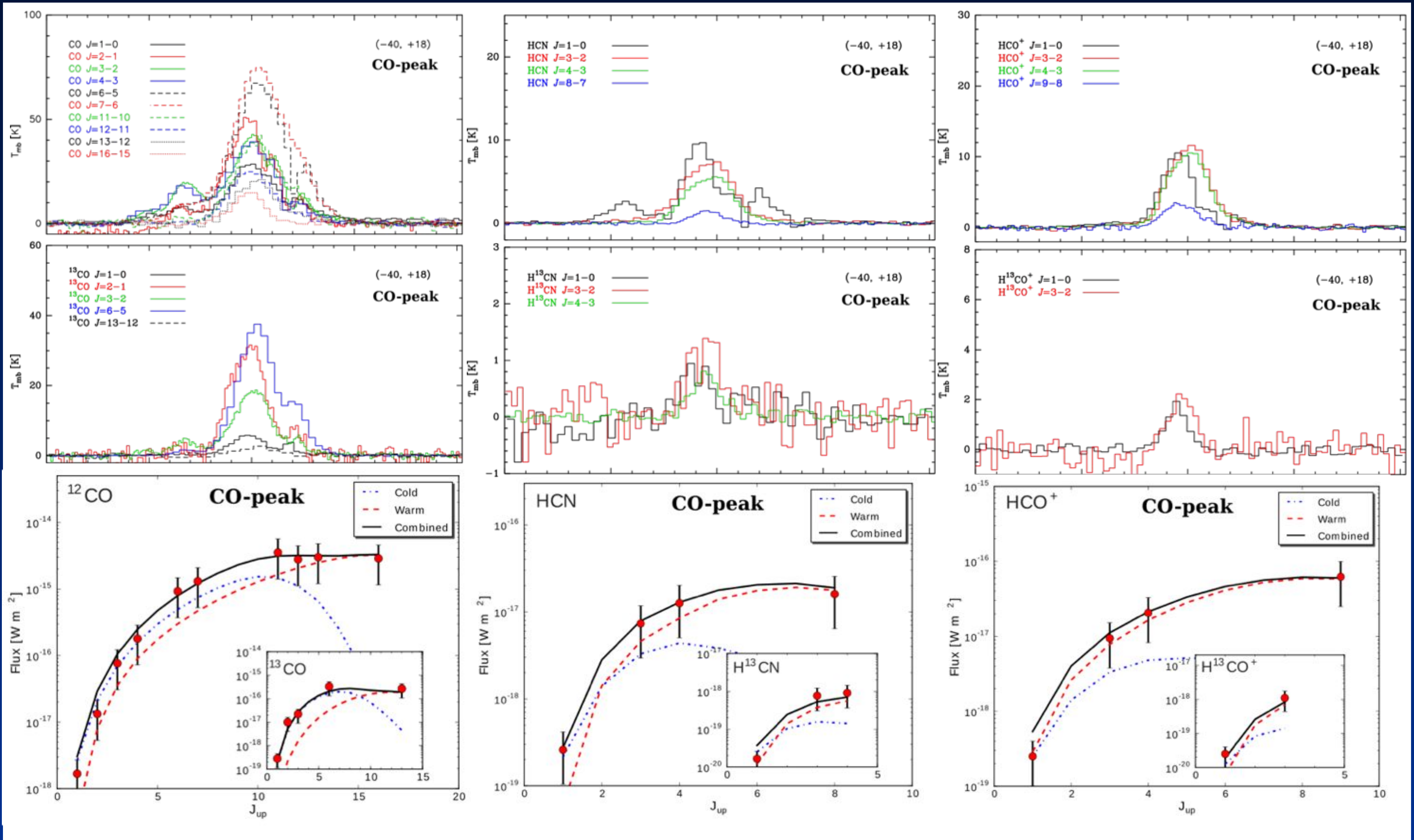


Line Spectral Energy Distributions (LSEDs) - III



Line Spectral Energy Distributions (LSEDs)

Line intensities (from Gaussian fit)



Excitation Conditions at Selected Positions

CO-peak

Parameter	CO	HCN	HCO^+
$\Phi_{cold}(^{12}C)$	0.50 ± 0.05	0.40 ± 0.05	0.40 ± 0.04
$n_{cold}(H_2)$ [cm^{-3}]	4.80 ± 0.61	4.80 ± 0.46	4.80 ± 0.58
T_{cold} [K]	90.00 ± 12.59	90.00 ± 8.21	90.00 ± 10.18
N_{cold} [cm^{-2}]	18.80 ± 0.35	15.30 ± 0.95	14.40 ± 1.33
$\Phi_{warm}(^{12}C)$	0.10 ± 0.01	0.10 ± 0.01	0.10 ± 0.01
$n_{warm}(H_2)$ [cm^{-3}]	5.70 ± 0.35	5.70 ± 0.62	5.70 ± 0.50
T_{warm} [K]	240.00 ± 29.77	240.00 ± 26.55	240.00 ± 26.54
N_{warm} [cm^{-2}]	18.50 ± 1.23	15.30 ± 1.10	15.10 ± 0.87
$\Phi_{cold}(^{13}C)$	0.50 ± 0.06	0.40 ± 0.04	0.40 ± 0.04
$\Phi_{warm}(^{13}C)$	0.10 ± 0.01	0.10 ± 0.01	0.10 ± 0.01
$\Delta V(^{12}C)$ [km s^{-1}]	4.60	4.60	4.30
$\Delta V(^{13}C)$ [km s^{-1}]	3.90	3.60	3.20

HCN-peak

Parameter	CO	HCN	HCO^+
$\Phi_{cold}(^{12}C)$	1.00 ± 0.09	0.40 ± 0.05	0.40 ± 0.05
$n_{cold}(H_2)$ [cm^{-3}]	4.50 ± 0.47	4.50 ± 0.47	4.50 ± 0.46
T_{cold} [K]	40.00 ± 3.78	40.00 ± 5.37	40.00 ± 4.83
N_{cold} [cm^{-2}]	18.90 ± 1.12	16.60 ± 1.06	16.40 ± 1.08
$\Phi_{warm}(^{12}C)$	0.35 ± 0.04	0.15 ± 0.01	0.15 ± 0.02
$n_{warm}(H_2)$ [cm^{-3}]	6.00 ± 0.73	6.00 ± 0.52	6.00 ± 0.48
T_{warm} [K]	130.00 ± 11.59	130.00 ± 15.33	130.00 ± 14.03
N_{warm} [cm^{-2}]	18.40 ± 0.37	15.40 ± 0.54	15.20 ± 0.81
$\Phi_{cold}(^{13}C)$	1.00 ± 0.11	0.40 ± 0.05	0.40 ± 0.03
$\Phi_{warm}(^{13}C)$	0.35 ± 0.04	0.15 ± 0.02	0.15 ± 0.01
$\Delta V(^{12}C)$ [km s^{-1}]	4.60	7.50	6.00
$\Delta V(^{13}C)$ [km s^{-1}]	3.50	3.90	3.70

PDR

Parameter	CO	HCN	HCO^+
$\Phi_{cold}(^{12}C)$	0.90 ± 0.07	0.35 ± 0.04	0.35 ± 0.04
$n_{cold}(H_2)$ [cm^{-3}]	5.30 ± 0.36	5.30 ± 0.49	5.30 ± 0.62
T_{cold} [K]	60.00 ± 5.32	60.00 ± 6.82	60.00 ± 7.09
N_{cold} [cm^{-2}]	18.95 ± 0.47	15.40 ± 0.85	14.80 ± 1.13
$\Phi_{warm}(^{12}C)$	0.20 ± 0.01	0.15 ± 0.02	0.15 ± 0.02
$n_{warm}(H_2)$ [cm^{-3}]	5.80 ± 0.37	5.80 ± 0.65	5.80 ± 0.56
T_{warm} [K]	110.00 ± 11.56	110.00 ± 12.33	110.00 ± 13.42
N_{warm} [cm^{-2}]	18.60 ± 0.31	15.10 ± 1.10	14.70 ± 1.11
$\Phi_{cold}(^{13}C)$	0.90 ± 0.09	0.35 ± 0.04	0.35 ± 0.04
$\Phi_{warm}(^{13}C)$	0.20 ± 0.02	0.15 ± 0.02	0.15 ± 0.02
$\Delta V(^{12}C)$ [km s^{-1}]	4.30	5.00	4.50
$\Delta V(^{13}C)$ [km s^{-1}]	4.30	3.80	3.90

M17-W

Parameter	CO	HCN	HCO^+
$\Phi_{cold}(^{12}C)$	1.00 ± 0.00	0.80 ± 0.06	0.80 ± 0.09
$n_{cold}(H_2)$ [cm^{-3}]	4.10 ± 0.00	4.10 ± 0.35	4.10 ± 0.49
T_{cold} [K]	60.00 ± 0.00	60.00 ± 5.17	60.00 ± 7.12
N_{cold} [cm^{-2}]	19.00 ± 0.00	16.20 ± 0.53	15.40 ± 1.01
$\Phi_{warm}(^{12}C)$	0.40 ± 0.00	0.20 ± 0.02	0.20 ± 0.02
$n_{warm}(H_2)$ [cm^{-3}]	5.80 ± 0.00	5.80 ± 0.39	5.80 ± 0.54
T_{warm} [K]	80.00 ± 0.00	80.00 ± 8.61	80.00 ± 8.79
N_{warm} [cm^{-2}]	18.90 ± 0.00	15.10 ± 1.21	15.00 ± 0.56
$\Phi_{cold}(^{13}C)$	1.00 ± 0.00	0.80 ± 0.08	0.80 ± 0.09
$\Phi_{warm}(^{13}C)$	0.40 ± 0.00	0.20 ± 0.02	0.20 ± 0.02
$\Delta V(^{12}C)$ [km s^{-1}]	6.90	6.10	7.10
$\Delta V(^{13}C)$ [km s^{-1}]	5.50	6.10	4.40

Excitation Conditions at Selected Positions

CO-peak

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$\Delta V(^{12}C)$ [km s^{-1}]	4.60	4.60	4.30
$\Delta V(^{13}C)$ [km s^{-1}]	3.90	3.60	3.20

HCN-peak

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T_{cold} [K]	40.00 ± 3.78	40.00 ± 5.37	40.00 ± 4.83
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$\Delta V(^{12}C)$ [km s^{-1}]	4.60	7.50	6.00
$\Delta V(^{13}C)$ [km s^{-1}]	3.50	3.90	3.70

PDR

Parameter	CO	HCN	HCO^+
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$\Phi_{warm}(^{13}C)$	0.20 ± 0.02	0.15 ± 0.02	0.15 ± 0.02
$\Delta V(^{12}C)$ [km s^{-1}]	4.30	5.00	4.50
$\Delta V(^{13}C)$ [km s^{-1}]	4.30	3.80	3.90

Average Spectra

Parameter	CO	HCN	HCO^+
$\Phi_{cold}(^{12}C)$	1.00 ± 0.13	0.60 ± 0.07	0.60 ± 0.07
$n_{cold}(H_2)$ [cm^{-3}]	4.80 ± 0.25	4.80 ± 0.49	4.80 ± 0.54
T_{cold} [K]	42.00 ± 3.71	42.00 ± 3.91	42.00 ± 4.38
N_{cold} [cm^{-2}]	19.50 ± 0.48	15.40 ± 1.19	14.20 ± 0.88
$\Phi_{warm}(^{12}C)$	0.10 ± 0.01	0.10 ± 0.01	0.10 ± 0.01
$n_{warm}(H_2)$ [cm^{-3}]	6.00 ± 0.60	6.00 ± 0.77	6.00 ± 0.48
T_{warm} [K]	135.00 ± 8.46	135.00 ± 12.09	135.00 ± 15.51
N_{warm} [cm^{-2}]	18.10 ± 0.36	14.70 ± 0.94	14.40 ± 0.50
$\Phi_{cold}(^{13}C)$	1.00 ± 0.12	0.60 ± 0.06	0.60 ± 0.05
$\Phi_{warm}(^{13}C)$	0.10 ± 0.00	0.10 ± 0.01	0.10 ± 0.01
$\Delta V(^{12}C)$ [km s$^-$1]	8.00	6.00	6.00
$\Delta V(^{13}C)$ [km s$^-$1]	6.00	6.00	4.00

Energy Balance in the Cloudlets

Gravitational Energy

Magnetic Wave Energy

$\mathcal{M}_w = \mathcal{T}$ ← Equipartition with internal motions

$$\mathcal{P}_s + |\mathcal{W}| = \mathcal{M}_S + \mathcal{M}_w + 2\mathcal{T}$$

External Pressure (radiation pressure from stars)

Static Magnetic Energy

Kinetic Energy

$$P_{\rm star} = Q(H^0)\langle h\nu\rangle / 4\pi R_{\rm H}^2 ck$$

$R_{\rm H}$: distance from the star cluster to the position in the cloud

$\langle h\nu \rangle$: mean photon energy of an O star, assumed 15 eV

$$Q({\rm H}^0) = 2.39 \times 10^{50}\ {\rm s}^{-1}$$

Total luminosity by number of ionising H photons per second, at a distance of 1.98 kpc

Energy Balance in the Cloudlets

Gravitational Energy

Magnetic Wave Energy

$\mathcal{M}_w = \mathcal{T}$ ← Equipartition with internal motions

$$\mathcal{P}_s + |\mathcal{W}| = \mathcal{M}_S + \mathcal{M}_w + 2\mathcal{T}$$

External Pressure (radiation pressure from stars)

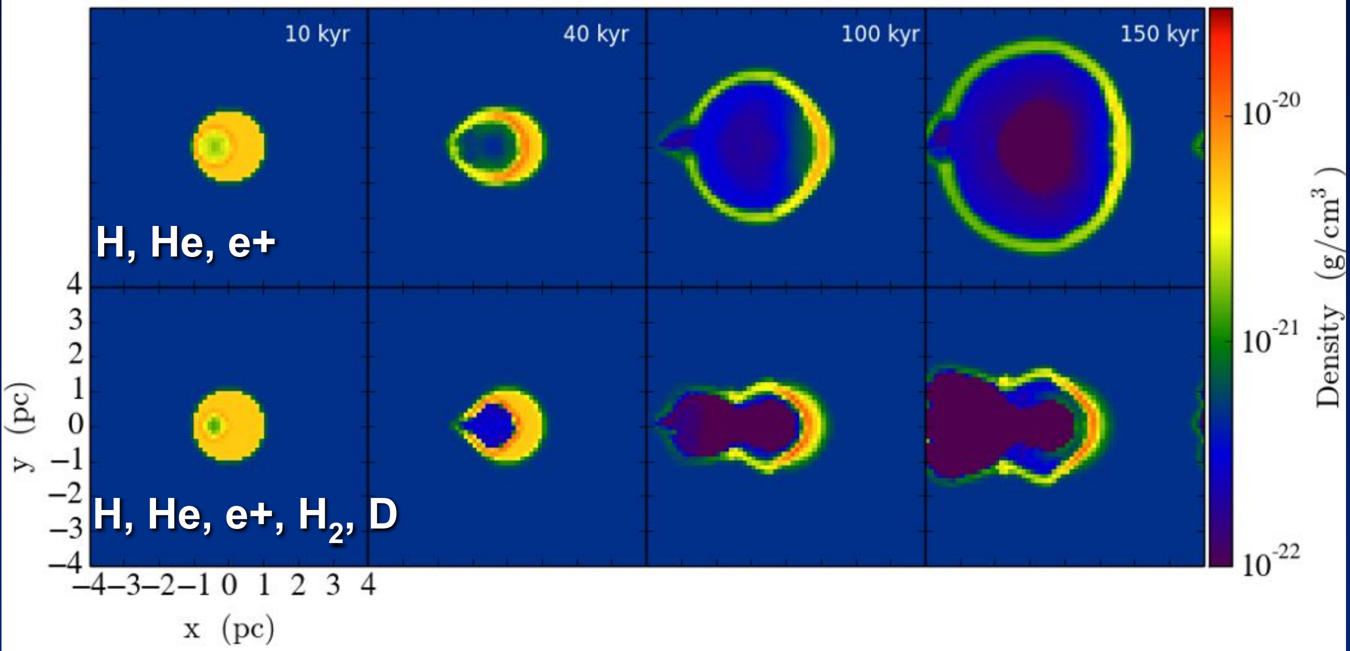
Static Magnetic Energy

Kinetic Energy

Position[a]	P_s Cold [ergs]	P_s Warm [ergs]	$\mathcal{M}_S$ Cold [ergs]	$\mathcal{M}_S$ Warm [ergs]	$\mathcal{M}_w$ Cold [ergs]	$\mathcal{M}_w$ Warm [ergs]	$2\mathcal{T}$ Cold [ergs]	$2\mathcal{T}$ Warm [ergs]	$\|W\|$ Cold [ergs]	$\|W\|$ Warm [ergs]
HCN-peak	1.3×10^{47}	2.3×10^{45}	1.0×10^{47}	1.0×10^{41}	1.1×10^{46}	1.3×10^{45}	2.3×10^{46}	2.5×10^{45}	1.2×10^{45}	1.5×10^{45}
CO-peak	2.0×10^{46}	1.3×10^{45}	6.6×10^{45}	1.7×10^{42}	4.6×10^{45}	4.6×10^{44}	9.1×10^{45}	9.1×10^{44}	4.9×10^{44}	7.8×10^{43}
PDR	2.4×10^{46}	2.5×10^{45}	1.6×10^{45}	4.6×10^{42}	1.0×10^{46}	1.0×10^{45}	2.0×10^{46}	2.0×10^{45}	7.1×10^{45}	4.9×10^{44}
M17-W	3.4×10^{48}	2.7×10^{46}	3.3×10^{48}	1.3×10^{43}	3.2×10^{46}	1.0×10^{46}	6.5×10^{46}	2.1×10^{46}	6.2×10^{44}	3.9×10^{45}

Ongoing Studies
MHD simulations with ENZO (enzo-project.org)

"Champaigne flow" (York 1986)

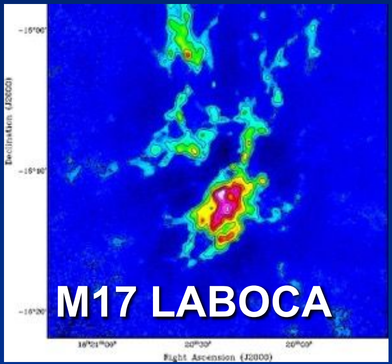


Box 8 pc (64^3 base grid)
Ambient T_K= 100 K
$n(H_2)$ = 290 cm^{-3}

Over density of 10 and 1 pc radius.

Radiation source:
10^{49} photon s^{-1} and T = 10^5 K black body spectrum.

No self gravity!



Pérez-Beaupuits et al., *in prep.*

Ongoing Studies

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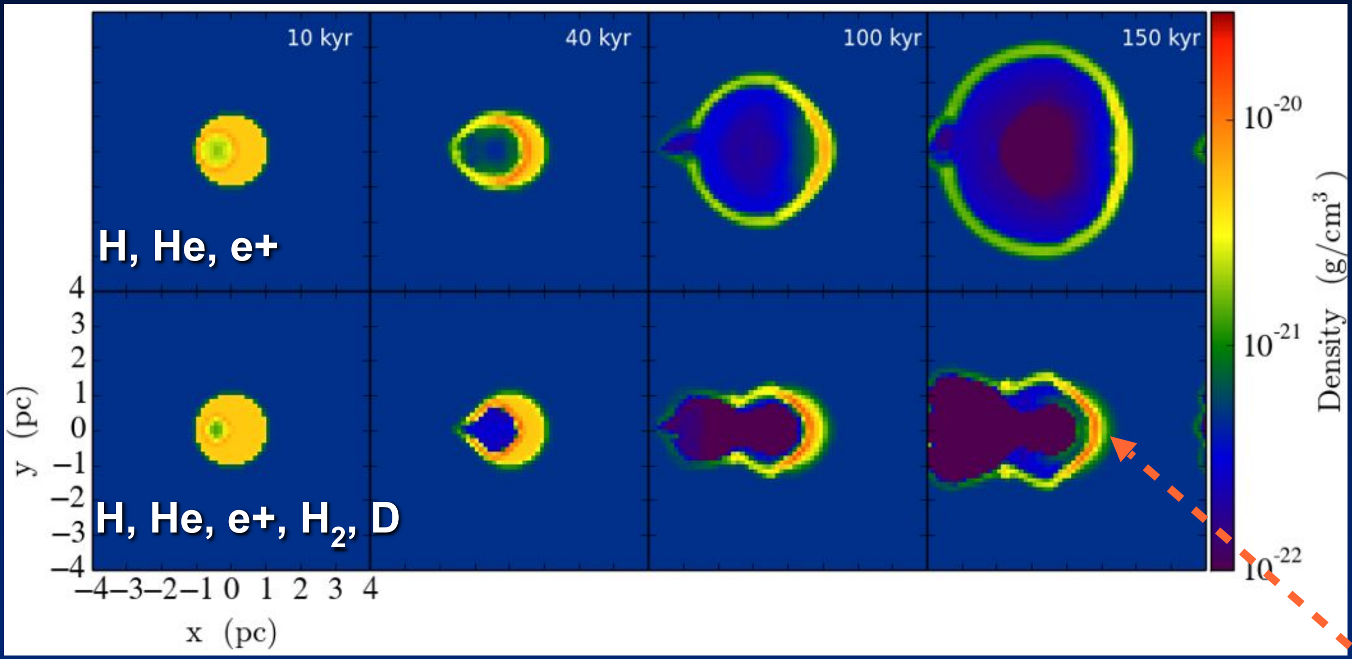
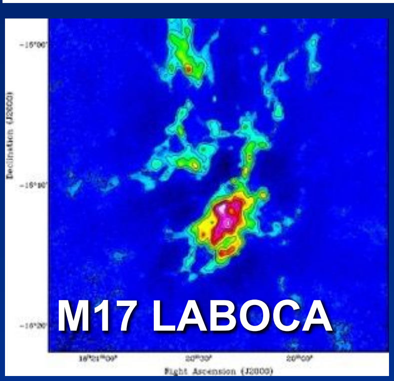


Box 8x8 pc
Ambient T_K= 100 K
$n(H_2)$ = 290 cm^{-3}

Over density of 10 and 1 pc radius.

Radiation source:
10^{49} photon s^{-1} and
T = 10^5 K black body spectrum.

No self gravity!



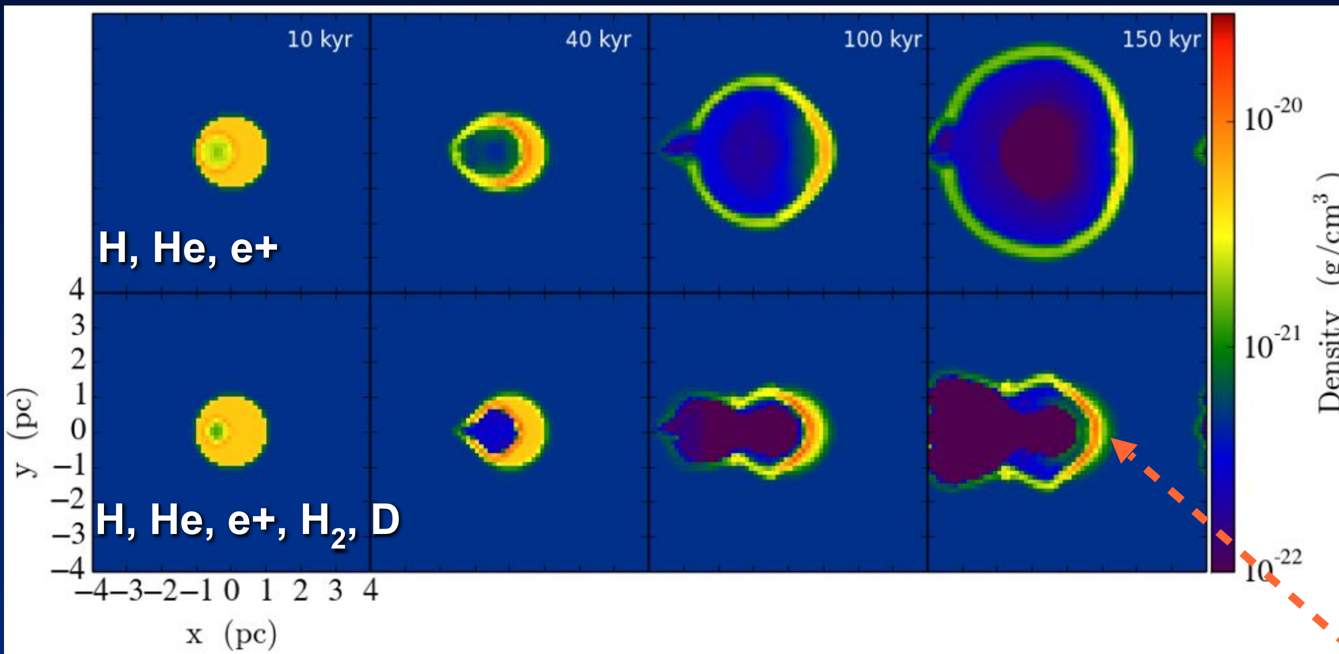
Pérez-Beaupuits et al., *in prep.*

- Radiation pressure!
- H_2 self-shielding

Ongoing Studies

MHD simulations with ENZO (enzo-project.org)

"Champaigne flow" (York 1986)



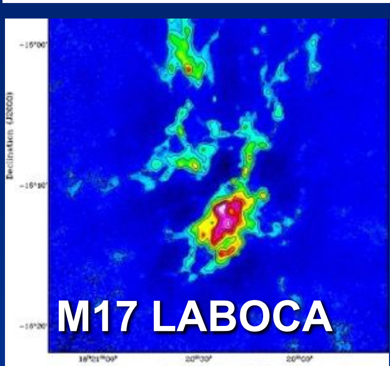
Box 8x8 pc
Ambient T_K = 100 K
$n(H_2)$ = 290 cm^{-3}

Over density of 10 and 1 pc radius.

Radiation source:
10^{49} photon s^{-1} and
T = 10^5 K black body spectrum.

No self gravity!

Pérez-Beaupuits et al., *in prep.*

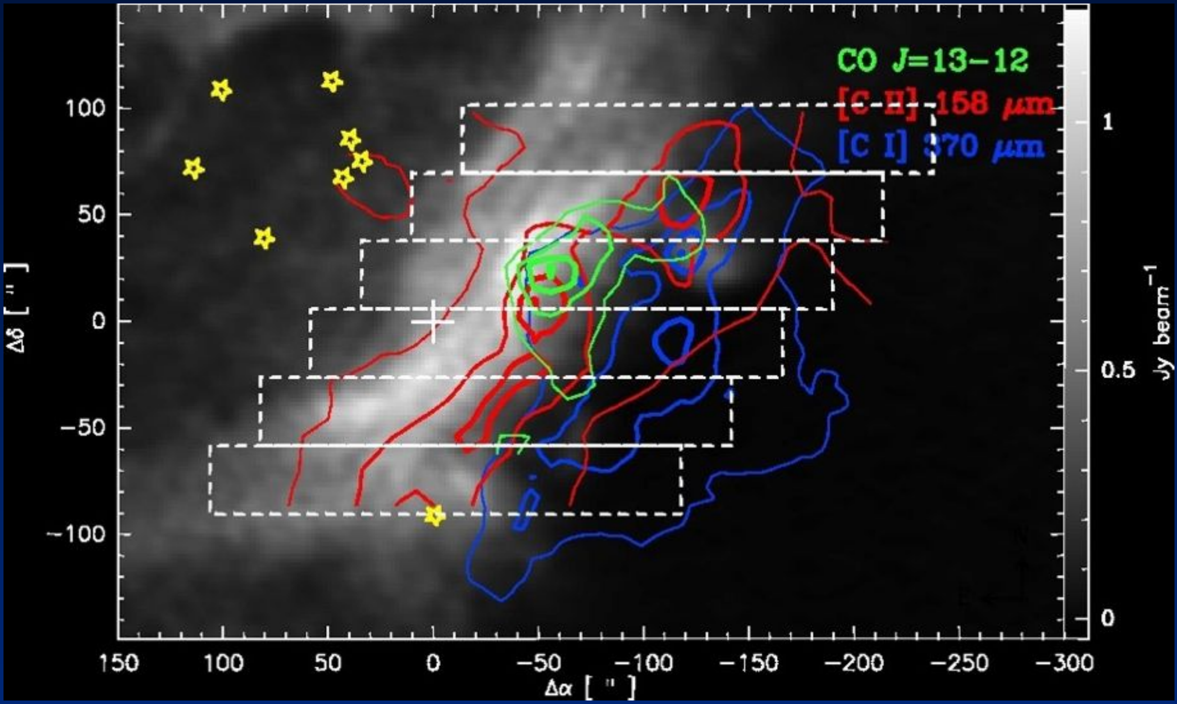


ure!
ng

NEXT!
O, C, N, ions, etc...
CO self-shielding (Visser, van Dishoeck, & Black 2009)

Previous Results

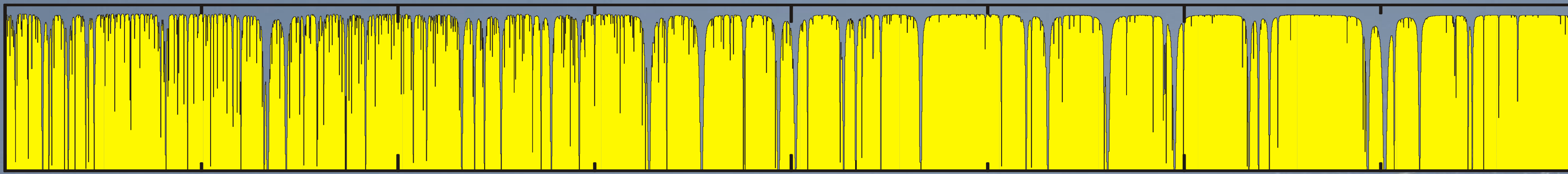
ESO NTT+SOFI



Ionizing energies:

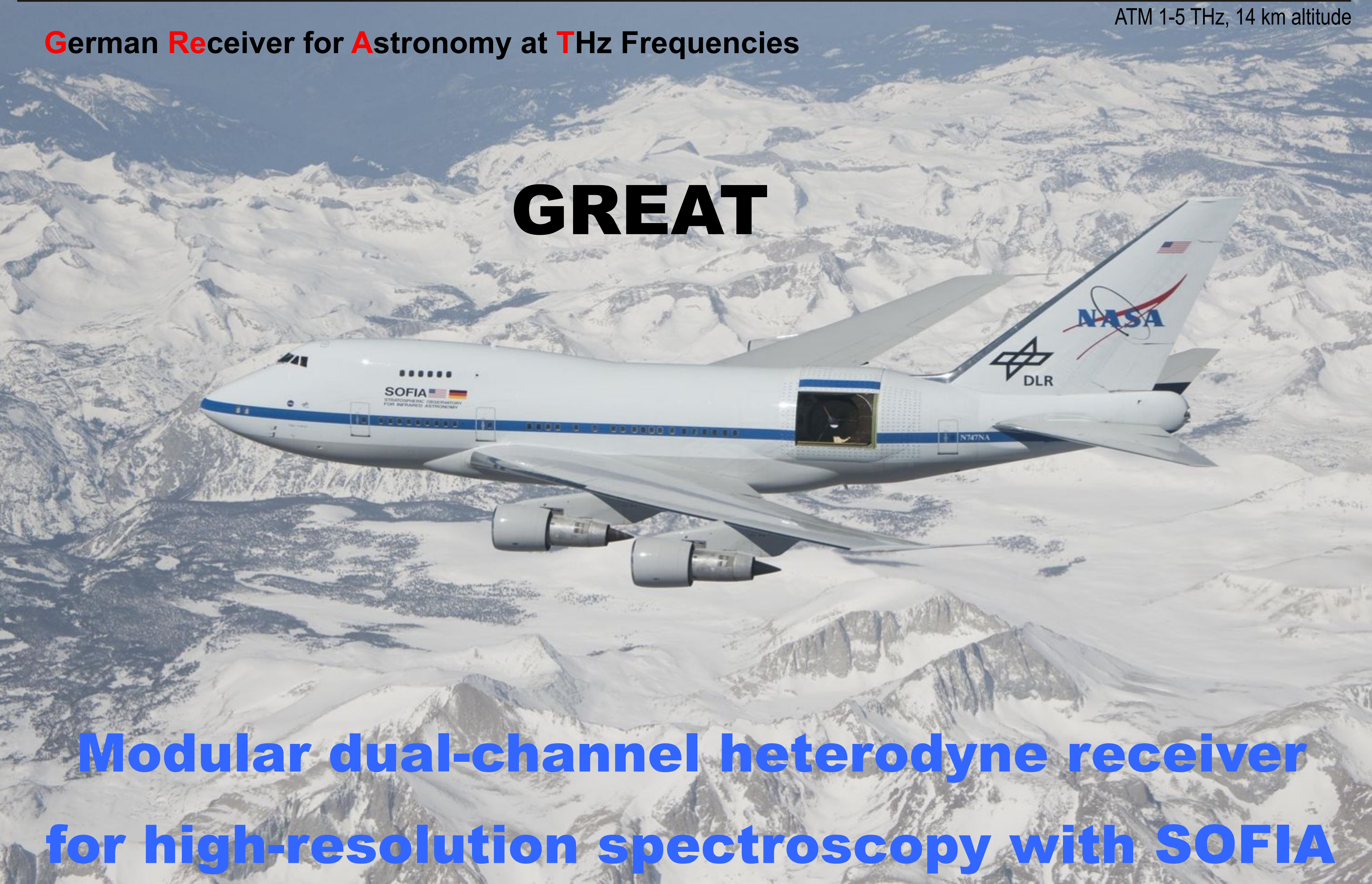
H: 13.598 eV
O: 13.61, 35.12 eV
C: 11.26, 24.38 eV
N: 14.53, 29.60 eV

(gray VLA HI 21cm image by Brogan & Troland 2001)
(contours by Pérez-Beaupuits et al. 2010, 2012)
(yelow O/B ionizing stars from Hanson et al. 1997)



German Receiver for Astronomy at THz Frequencies

GREAT

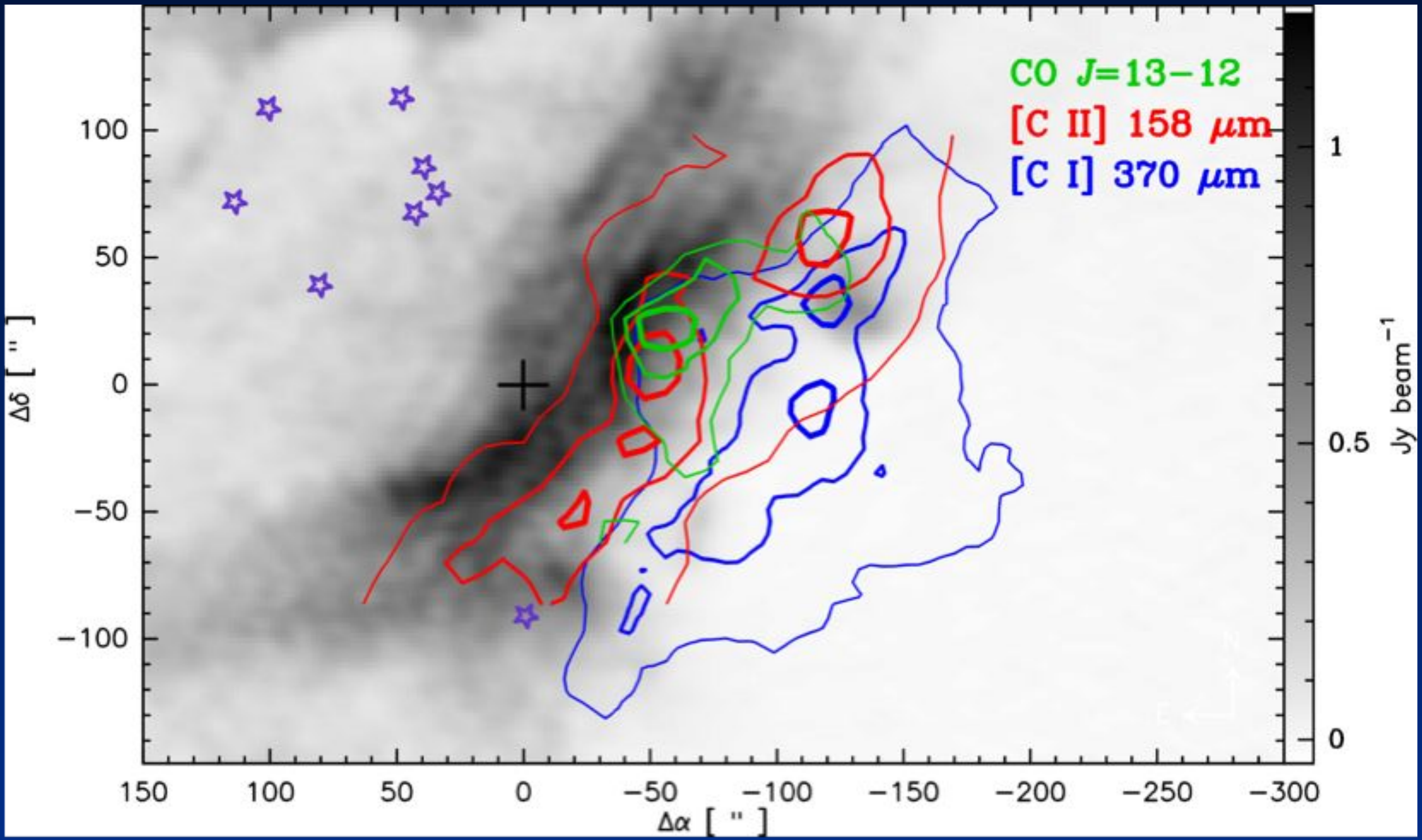


Modular dual-channel heterodyne receiver for high-resolution spectroscopy with SOFIA

SOFIA/GREAT Results

PDR stratification?

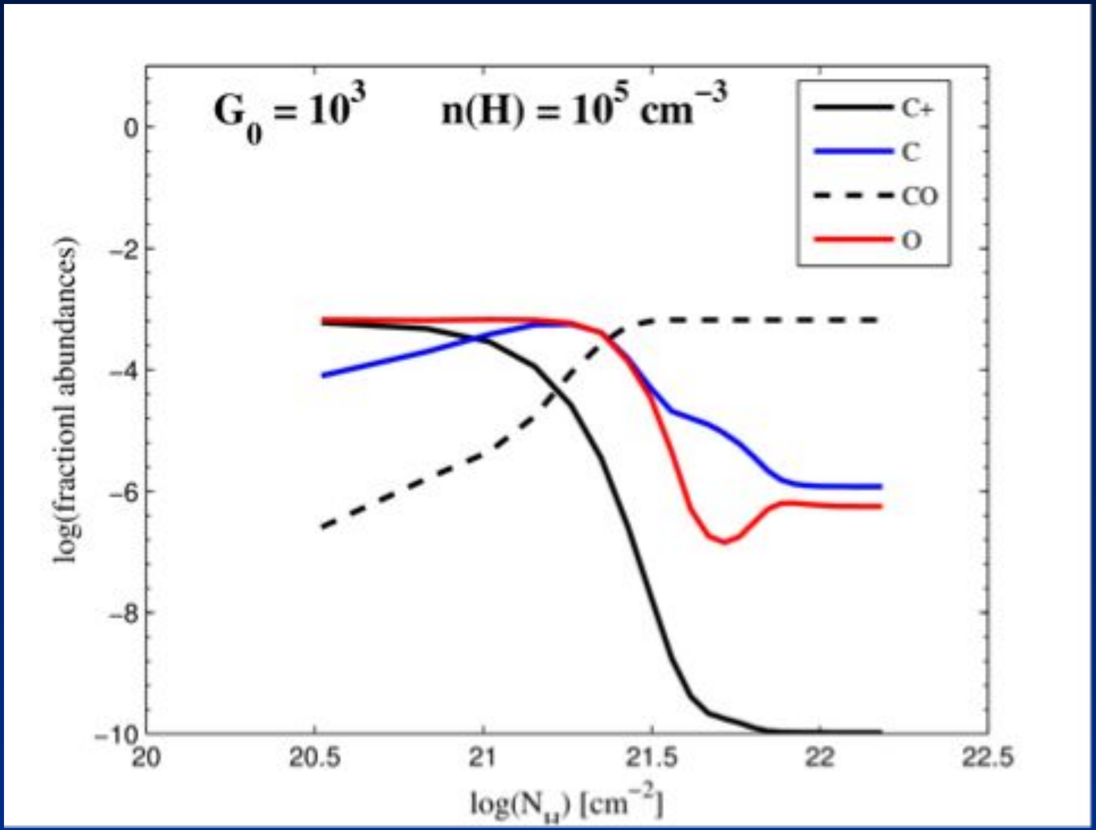
$C^+ \longrightarrow C \longrightarrow CO$



SOFIA/GREAT [O I] 63 μm

PDR scheme revisited

$C^+ \longrightarrow C/O \longrightarrow CO$



PDR model

(from Meijerink & Spaans 2005)