Ionized carbon tracing the assembly of molecular clouds

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and the FEEDBACK consortium

Based on data taken within the SOFIA legacy program FEEDBACK

March 23, 2022

- **SOFIA legacy program** to map the CII 158 µm and OI 63 µm lines with upGREAT in **11 Galactic star-forming** regions.

- **96 h** observing time observing runs from Palmdale (California) and Christchurch (New Zealand) + Cologne, Tahiti, Santiago… Observations will be finished in 2022.

- **German PI**: N. Schneider, **American PI**: A.G.G.M. Tielens

- Maps of size **200 -700 arcmin^2** with an angular resolution of **14” (CII)** and **6” (OI)** and a spectral resolution of <0.2 km/s.

- Objective is to study **stellar feedback from massive stars** on the interstellar medium: heating- and cooling processes, triggering of star-formation, and the dynamic formation and evolution of molecular clouds.

Quasi-static scenario

(e.g. Krumholz et al. 2005)

- ***Equilibrium*** between gravity, turbulence and magnetic fields.
- External increase of pressure or turbulence due to stellar feedback, spiral arm density waves leads to a ***slow, quasi-static growth of density*** randomly, leading to the formation of pockets of molecular gas.

Dynamic scenario

(e.g. Hartmann et al. 2001, Koyama & Inutsuka 2000, Vazquez-Semadeni et al. 2006)

- Large scale converging atomic/molecular flows, ***no equilibrium***.
- Formation of molecular clouds by a ***fast transition*** from the warm (T~ 5000K), neutral medium (WNM) to the cold (T~ 50-100K) neutral medium (CNM) through thermal instability in the shocked layers of diffuse gas collisions.

Colliding flows of atomic (HI) gas

Vazquez-Semadeni et al. 2007, 2008, 2009; Heitsch & Hartmann 2008; Clark et al. 2019, ….

Dobbs et al. 2020

$n \simeq 1\ cm^{-3}$
$T \simeq 30\text{-}100\ K$
$v \lesssim 10\ km/s$

$n \simeq 100\ cm^{-3}$
$T \simeq 100\ K$
$v \simeq 20\ km/s$

'soft collision' of atomic/molecular flows

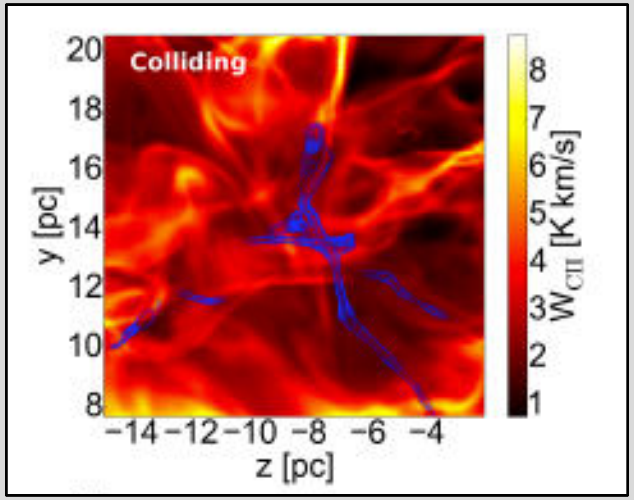
Schneider et al., Bonne et al.

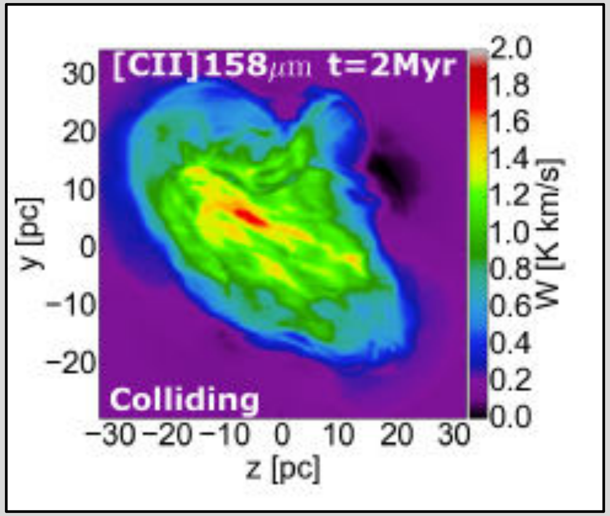
$n \simeq 100\ cm^{-3}$
$T \simeq 100\ K$
$v \lesssim 20\ km/s$

Cloud-cloud collisions (CCCs)

Fukui et al. 2014, 2015, 2016; Haworth et al. 2015a, 2015b; Bisbas et al. 2017, 2018; Wu et al., 2015, 2017

$n \gtrsim 100\ cm^{-3}$
$T \simeq 10 – 50\ K$
$v \gtrsim 10\ km/s$





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Advance Access publication 2019 April 20

Tracing the formation of molecular clouds via [C II], [C I], and CO emission

Paul C. Clark [1]★ Simon C. O. Glover,[2] Sarah E. Ragan [1] and Ana Duarte-Cabral [1]

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[2] *Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik, Albert-Ueberle-Str. 2, D-69120 Heidelberg, Germany*

Model:

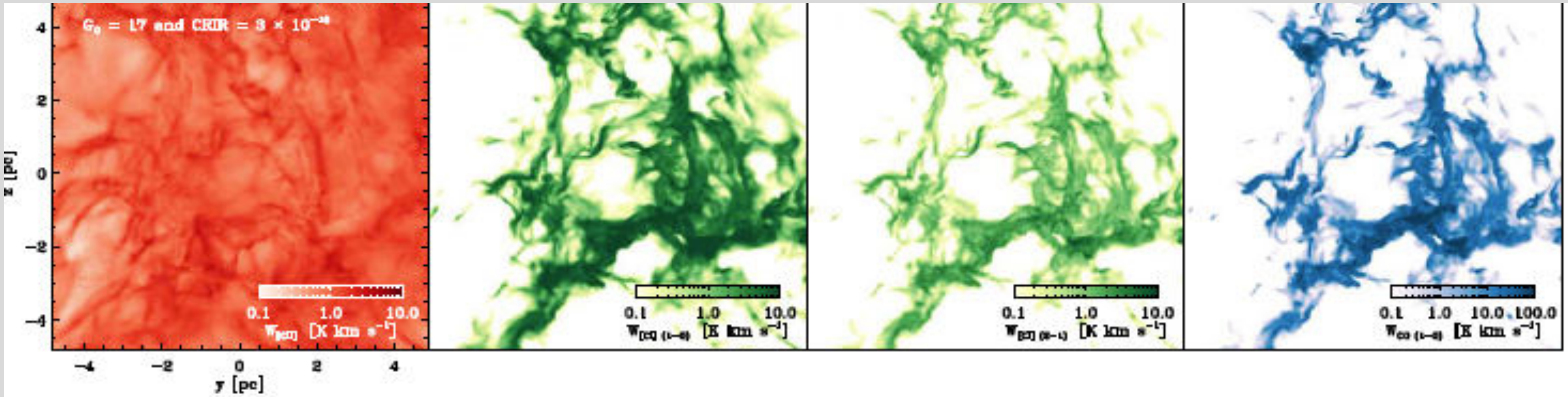
- MHD simulation with self-gravity
- Hydrogen, carbon, oxygen chemistry is treated. Post-processing with RADMC-3D
- $n=10\ cm^{-3}$, $M=10^4\ M_{sun}$, $r=19$ pc, $v_{coll}=3.75$ km/s, turbulence 1 km/s
- $G_o = 17$

Predictions:

CII comes mostly from the diffuse ISM within a narrow range of density (10 to a few $10^3\ cm^{-3}$) and temperature (a few 10 to 100 K).

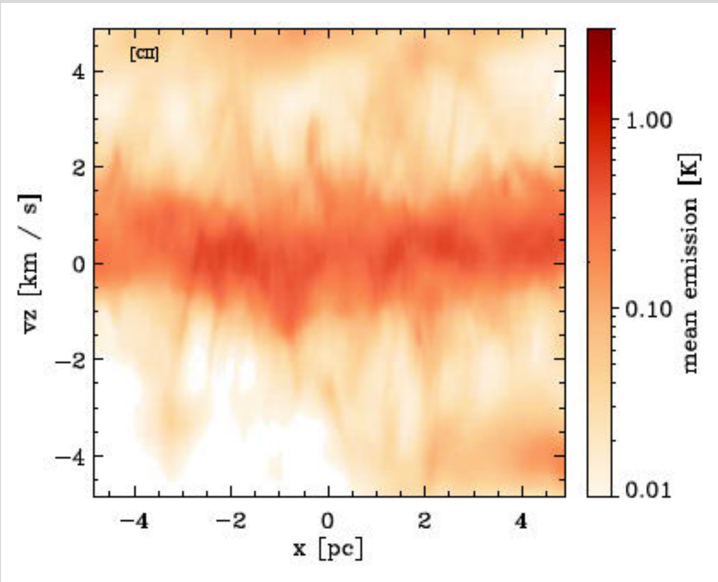
CII emission **more extended spatially and in velocity** than CO emission.
It can show emission that is not visible in CO ('CO-dark/poor') and CI.

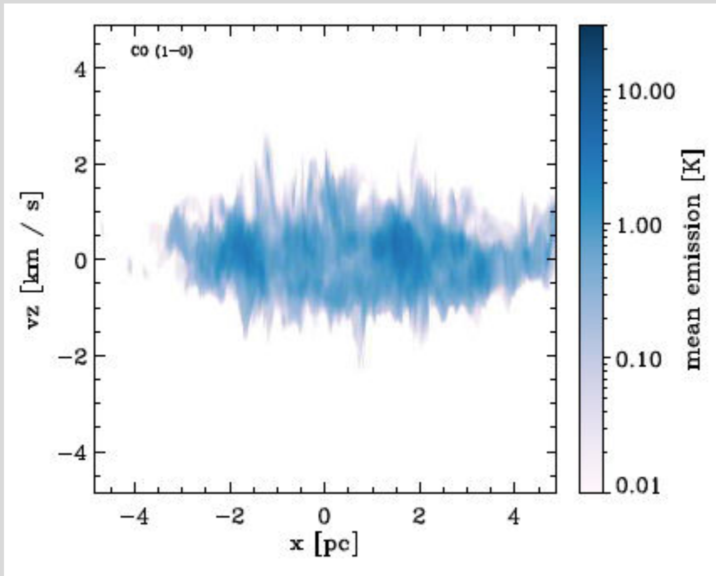
$G_o = 17$



CII CI 1-0 CI 2-1 CO 1-0

Position-velocity cuts





$G_o = 4$

- MHD, self-gravity
- PDR post-processing
- n=100 cm^{-3}, M= 9 10^4 M_{sun}, r=20 pc
- v_{coll} = 10 km/s,
- $v_{turbulence}$ = 5.2 km/s

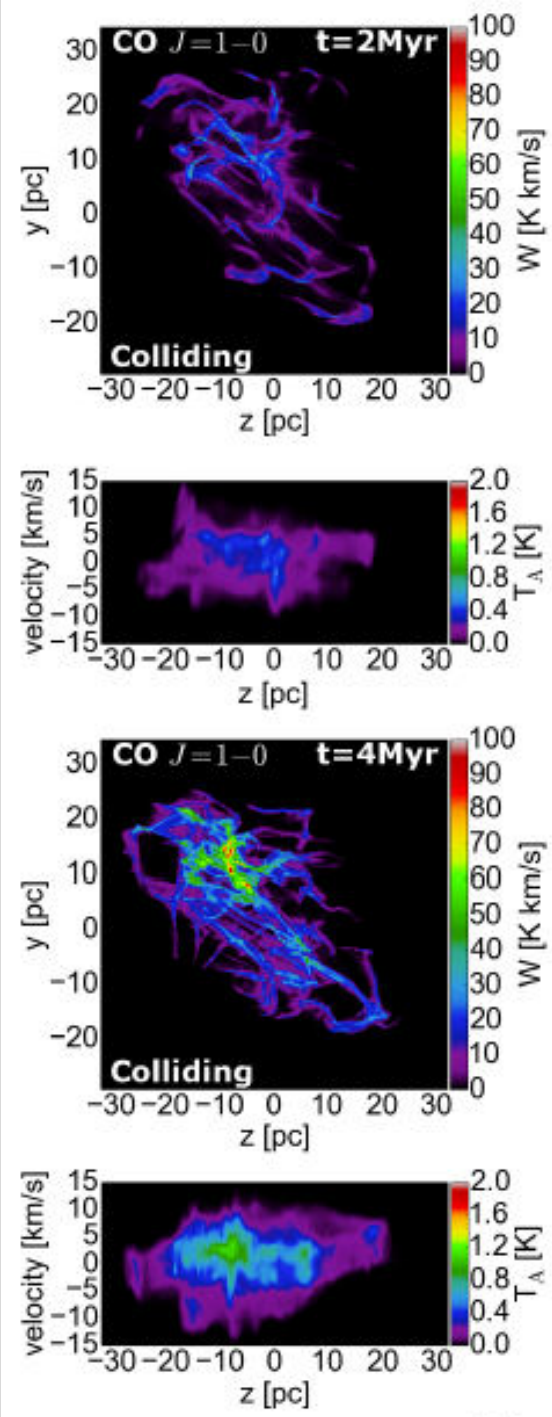
(Bisbas et al. 2017)

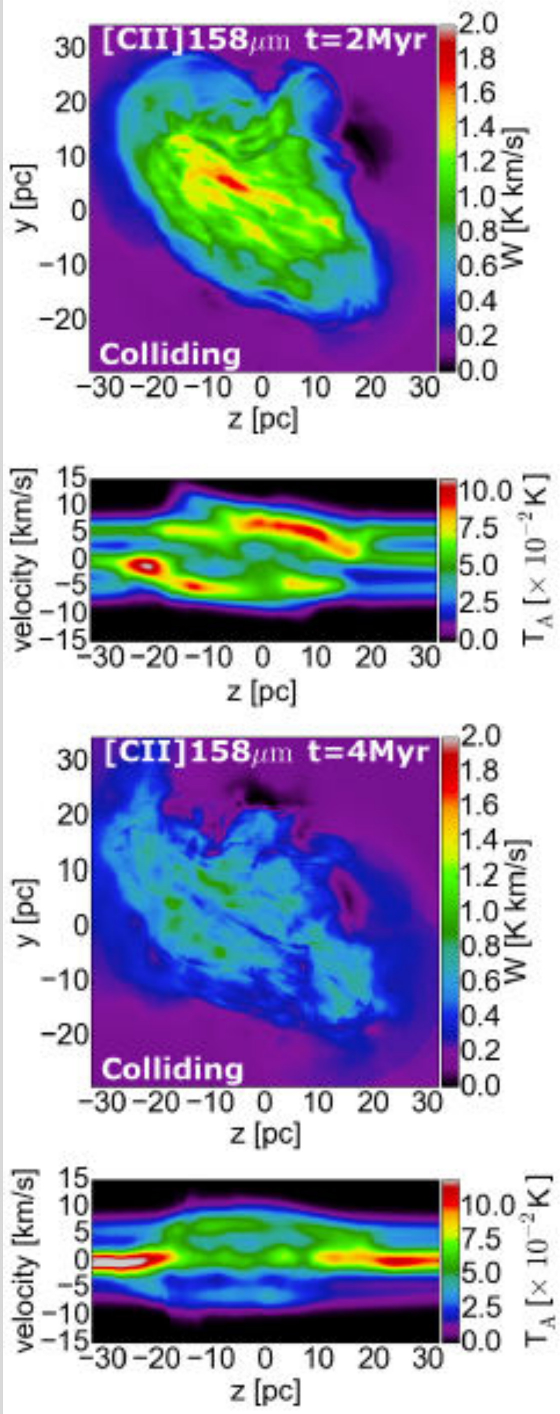
CII emission **more extended spatially and in velocity** than CO emission.

Two velocity components seen in CO and CII with a **bridge of emission** in between.

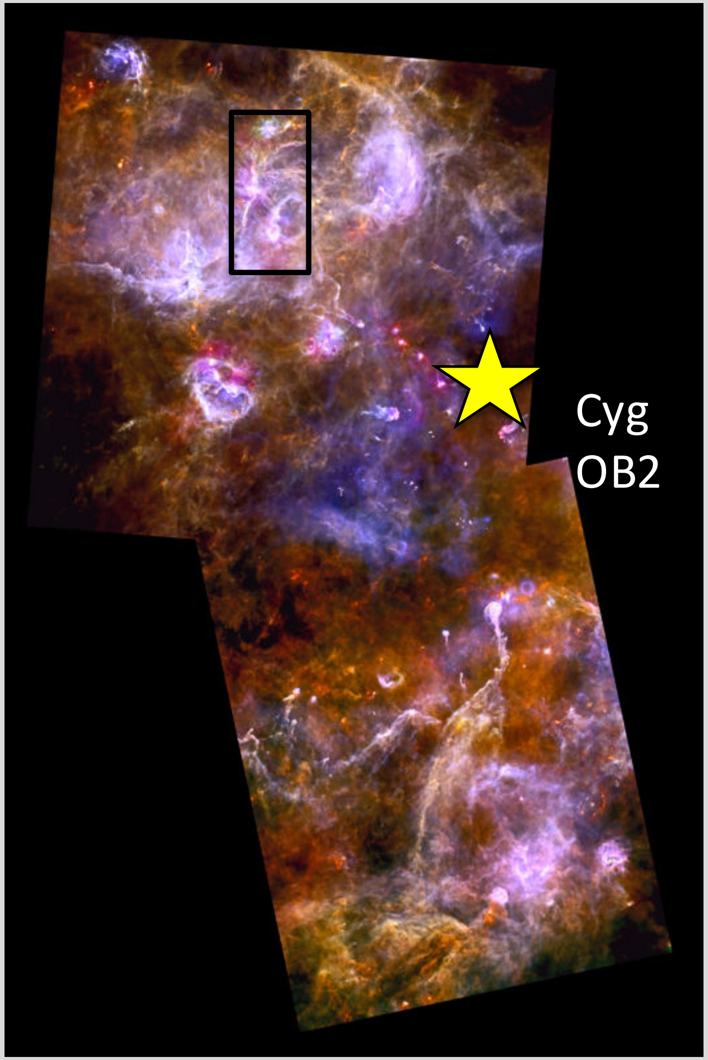
CCCs reported by Fukui et al., Dobashi et al. based on CO.

Position-velocity cuts

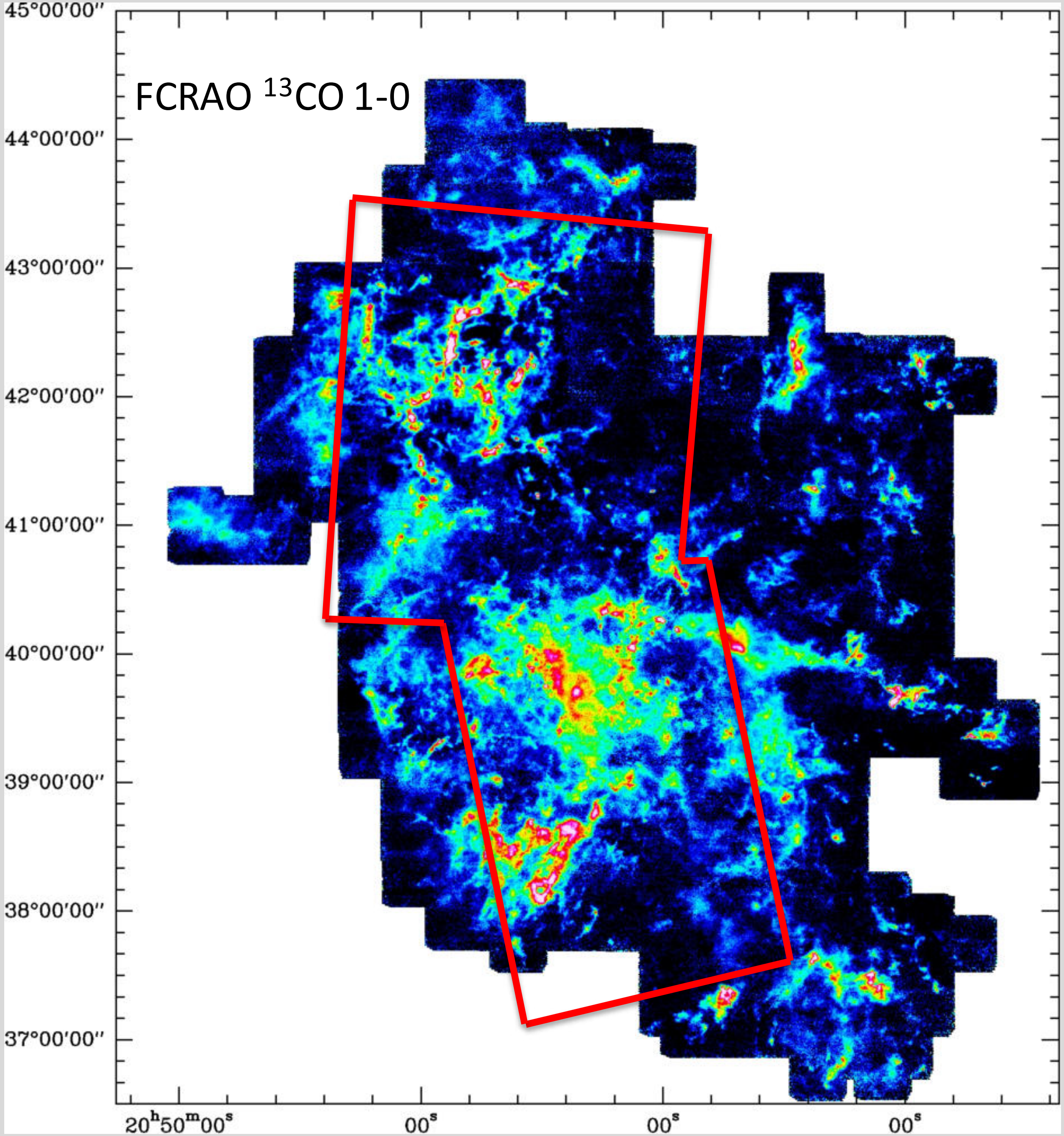




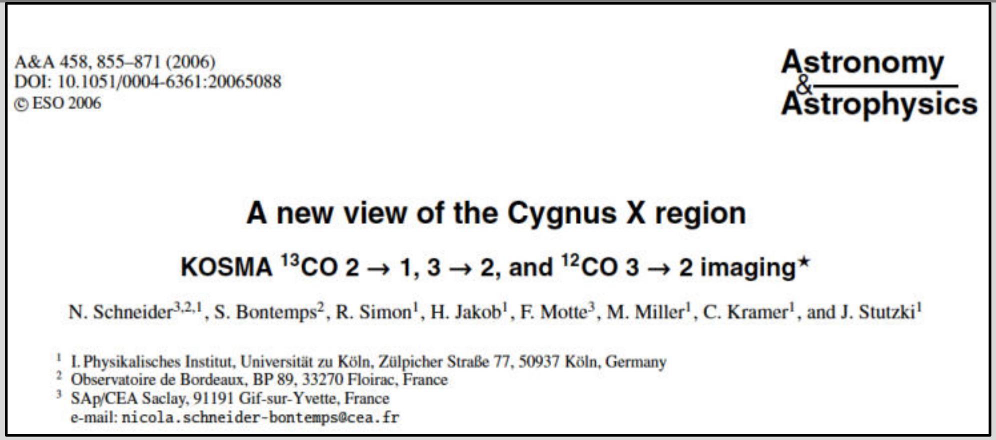
Herschel 70, 160, 250 µm (HOBYS)



Hennemann et al. 2012; Schneider et al. 2016a



Schneider, Bontemps, Simon et al. 2011; Schneider et al. 2016b



A&A 458, 855–871 (2006)
DOI: 10.1051/0004-6361:20065088

Astronomy & Astrophysics

A new view of the Cygnus X region

KOSMA ^{13}CO 2 → 1, 3 → 2, and ^{12}CO 3 → 2 imaging*

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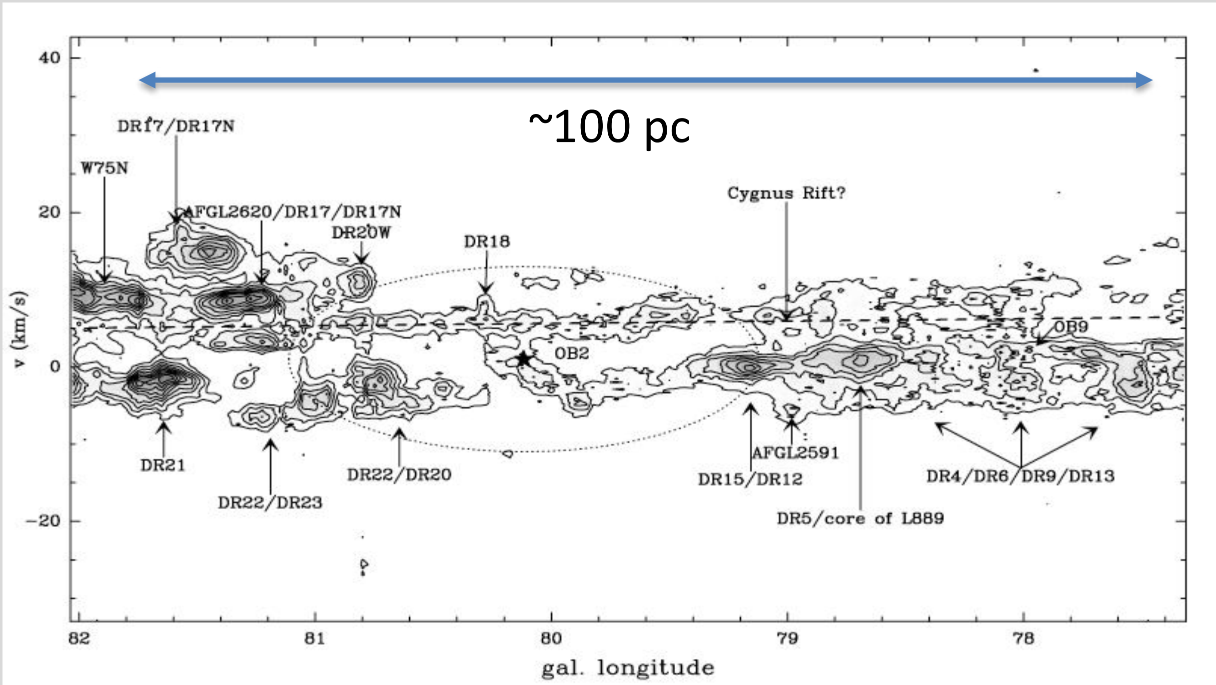
- The Cygnus X molecular complex is not a line-of-sight effect (Wendker et al. 1984, 1991) but forms a ***single star forming region*** (despite the very large velocity differences of -5 to 18 km/s in CO).
- At that time, it was not clear how such large relative velocities could co-exist spatially inside a single event of star formation.



Schneider et al. 2010, Bonne et al. 2022:

- DR21 ridge initially formed by colliding HI flows.
- Gravity then took over, mass accretion by filaments, moderated by magnetic fields.

Herschel (70, 160,250 µm)

A&A 520, A49 (2010)
DOI: 10.1051/0004-6361/201014481

Astronomy & Astrophysics

Dynamic star formation in the massive DR21 filament

N. Schneider[1], T. Csengeri[1], S. Bontemps[2], F. Motte[1], R. Simon[3], P. Hennebelle[4], C. Federrath[5], and R. Klessen[5,6]

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Dickel et al. 1978, Dobashi et al. 2019

- DR21 ridge and W75N are in collision (CCCs)

Dickel et al. 1978

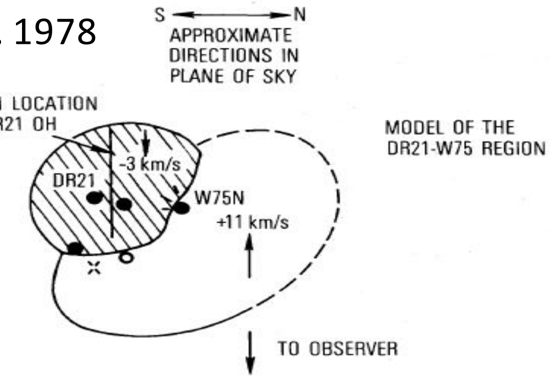
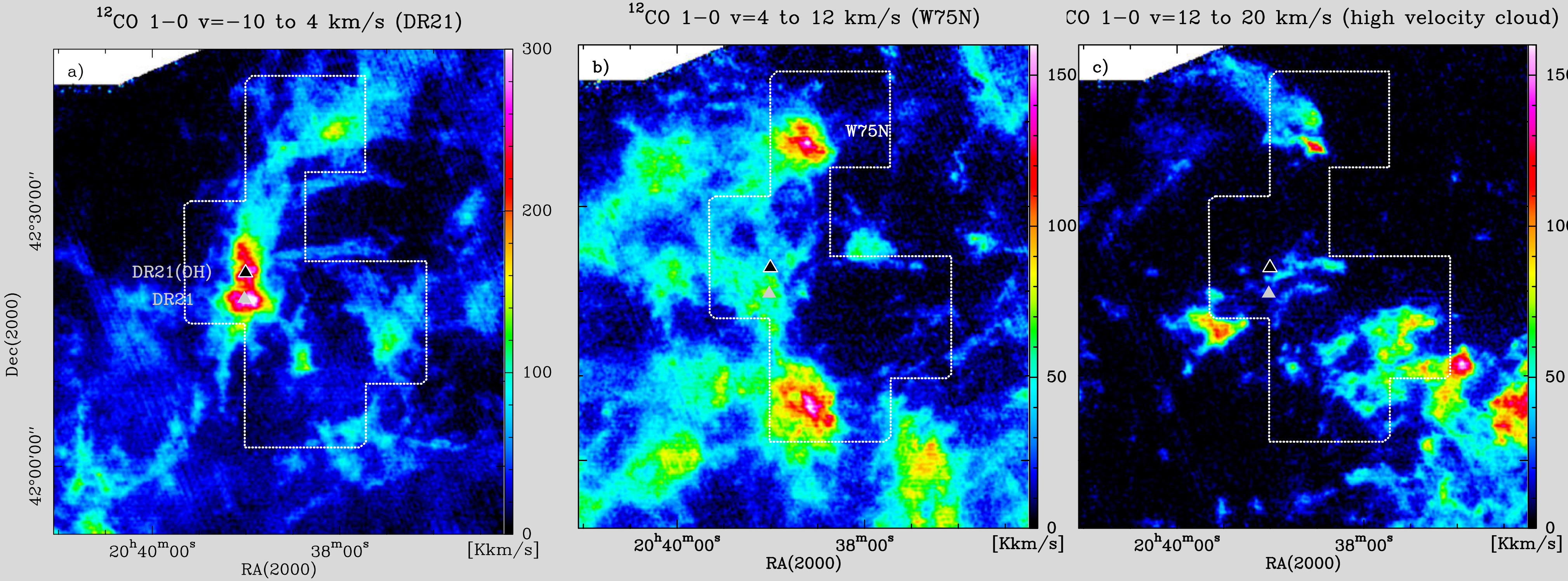


FIG. 8.—Schematic model of the DR 21–W75 region showing a possible configuration of the two large colliding clouds and the various condensations within them. The filled circles represent regions of enhanced temperature and density, the groups of short lines represent heating effects, and the open circle represents a region of increased line width.

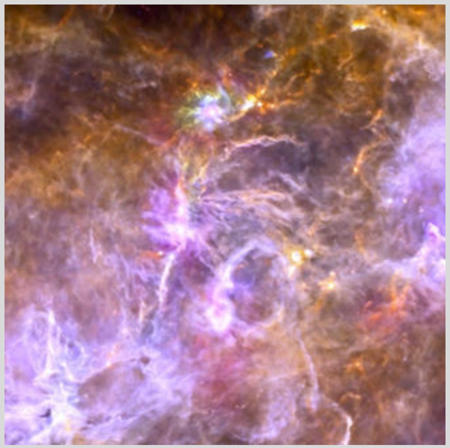
- 3 km/s 9 km/s 15 km/s



DR21-cloud 1.5+-0.1 kpc

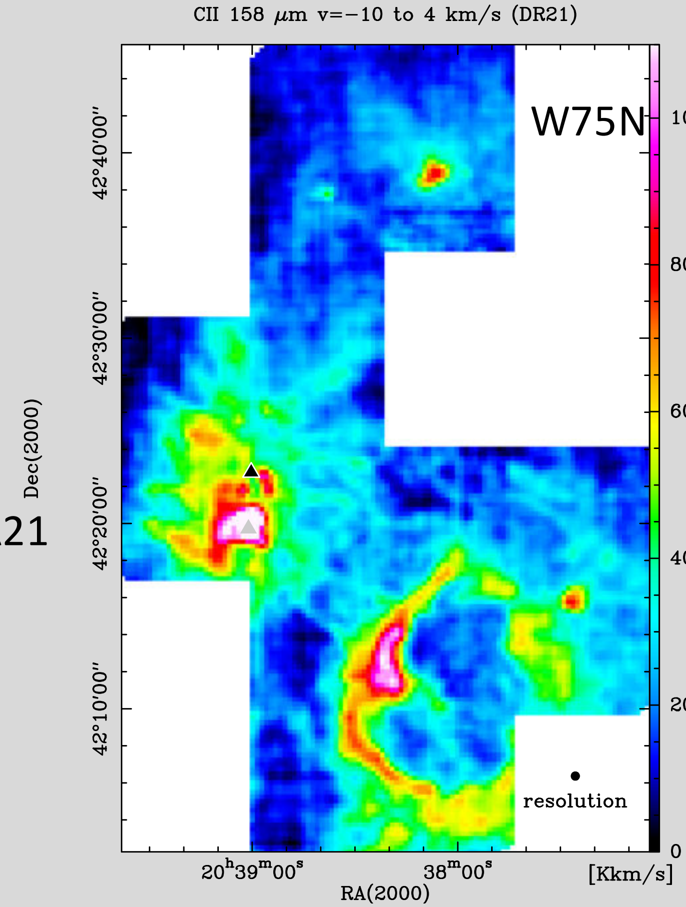
W75N-cloud 1.3+-0.1 kpc

high-velocity clouds <1.5 kpc

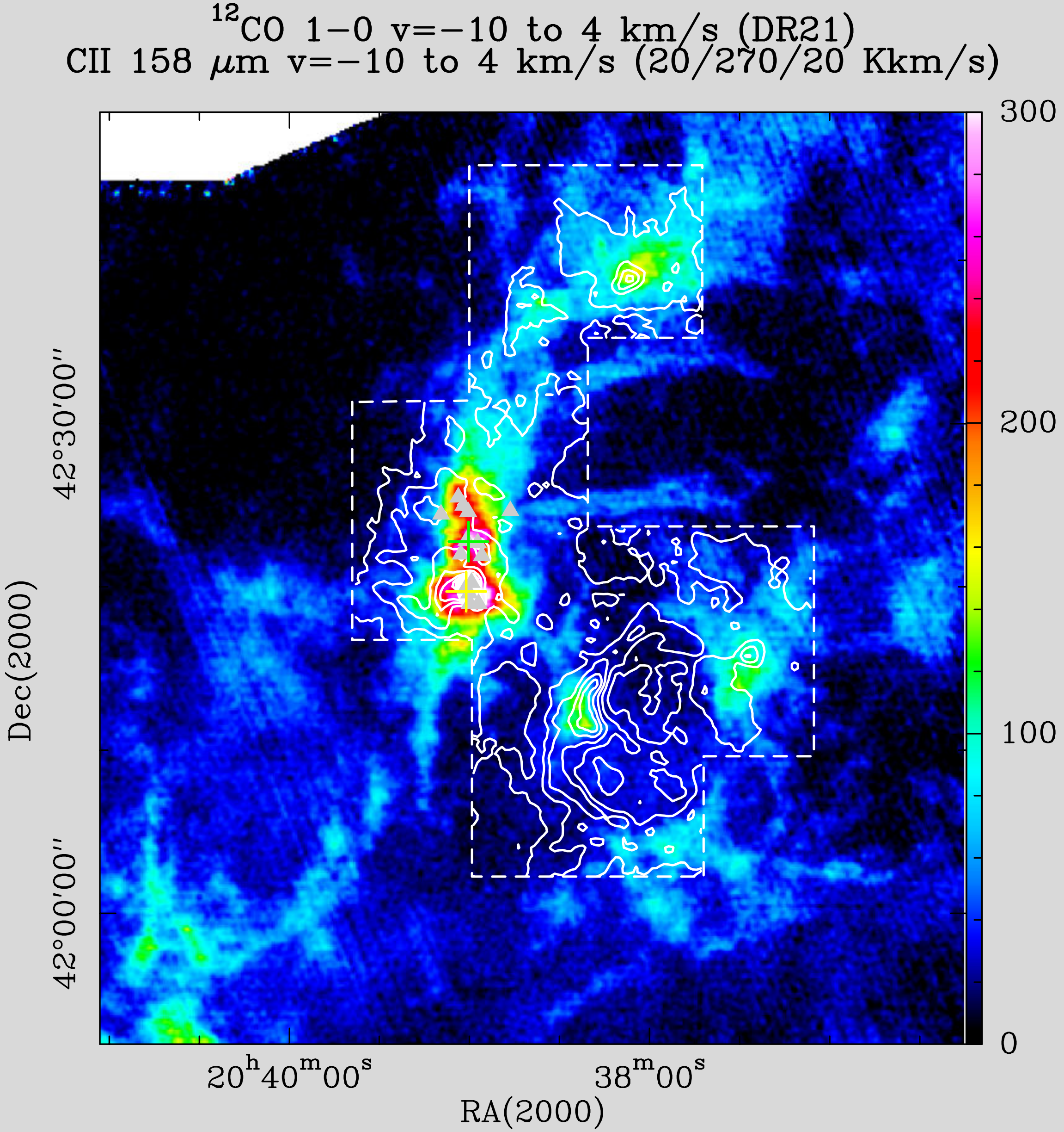


Distances from maser parallax (Rygl et al. 2012).

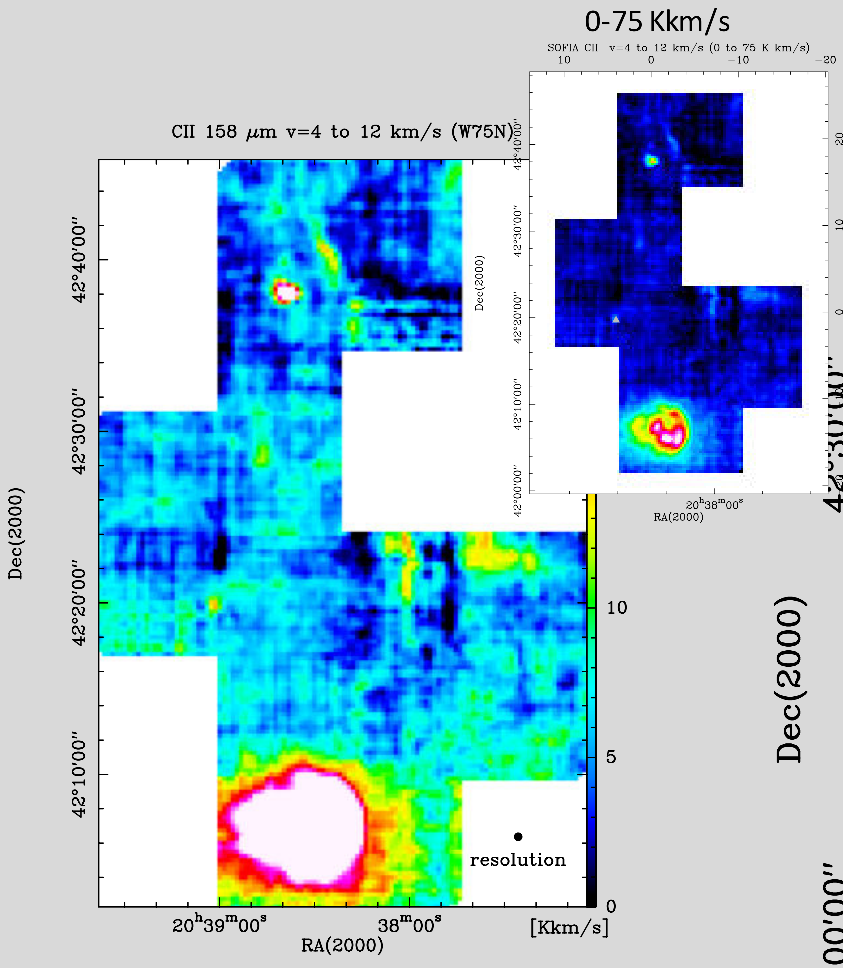
- Extended low-level CII correlating well with PAH (filaments).
- CII peaks (PDRs) due to local sources.

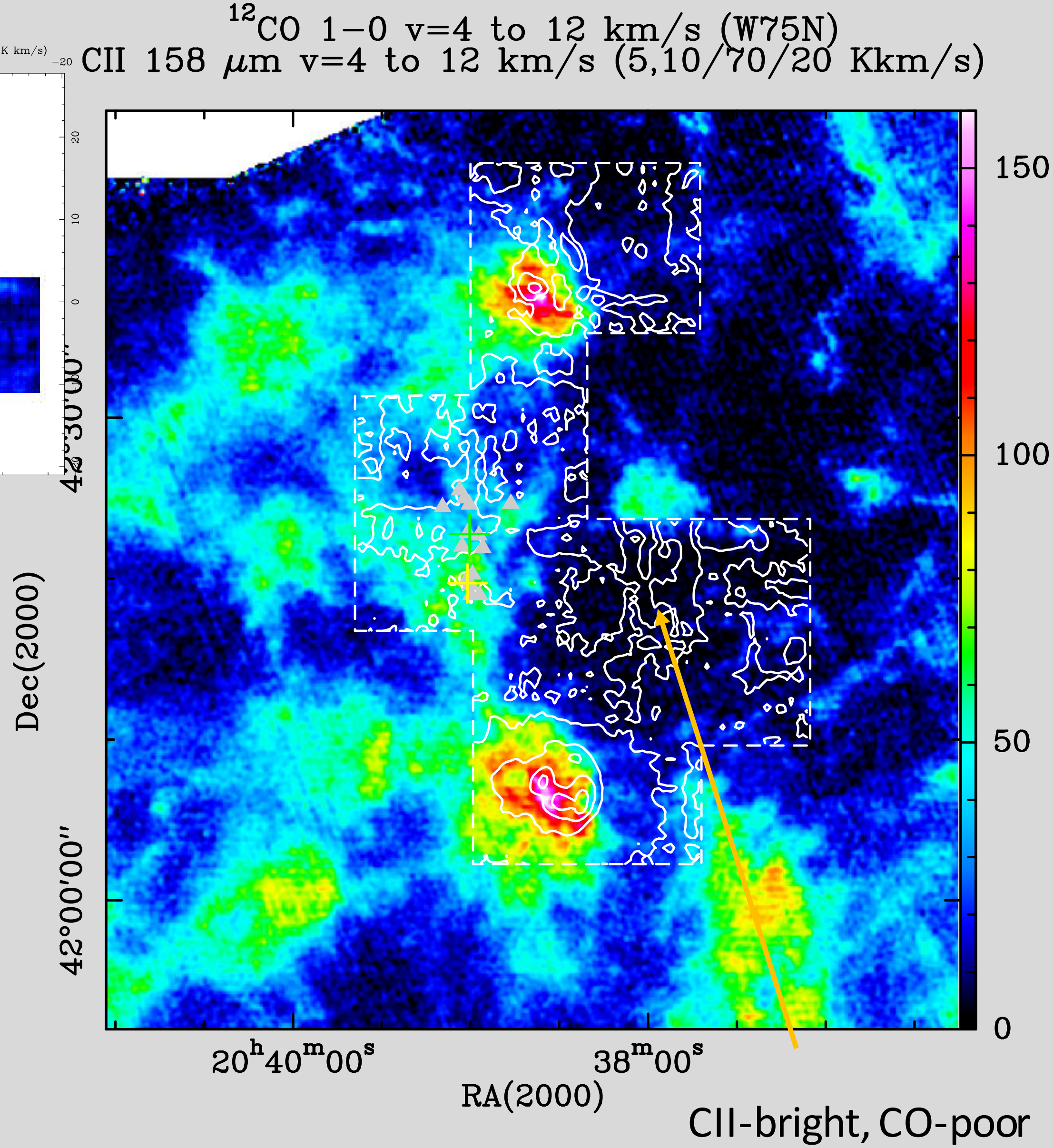


Diamond Ring

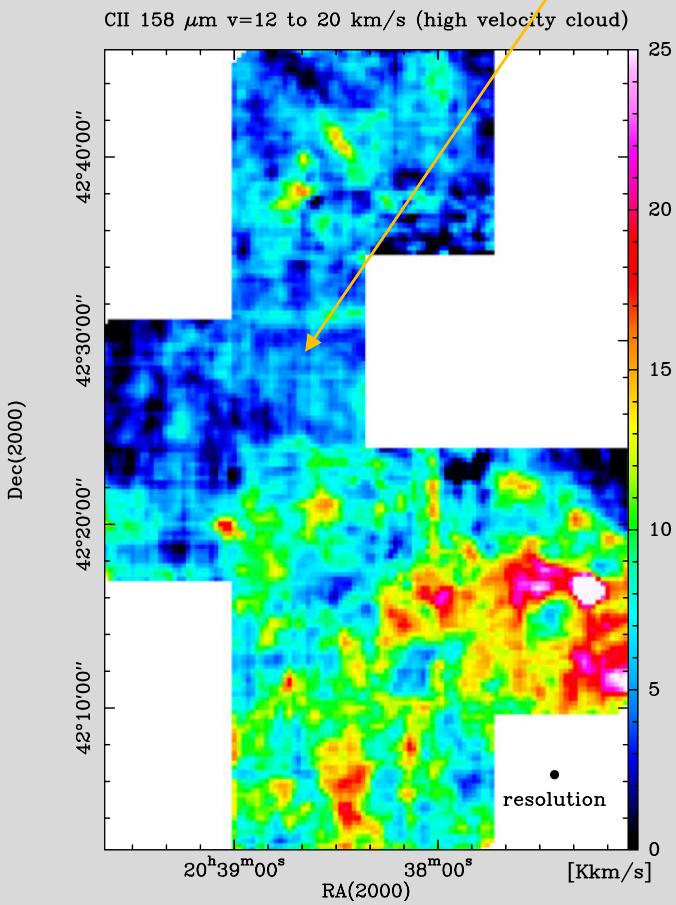


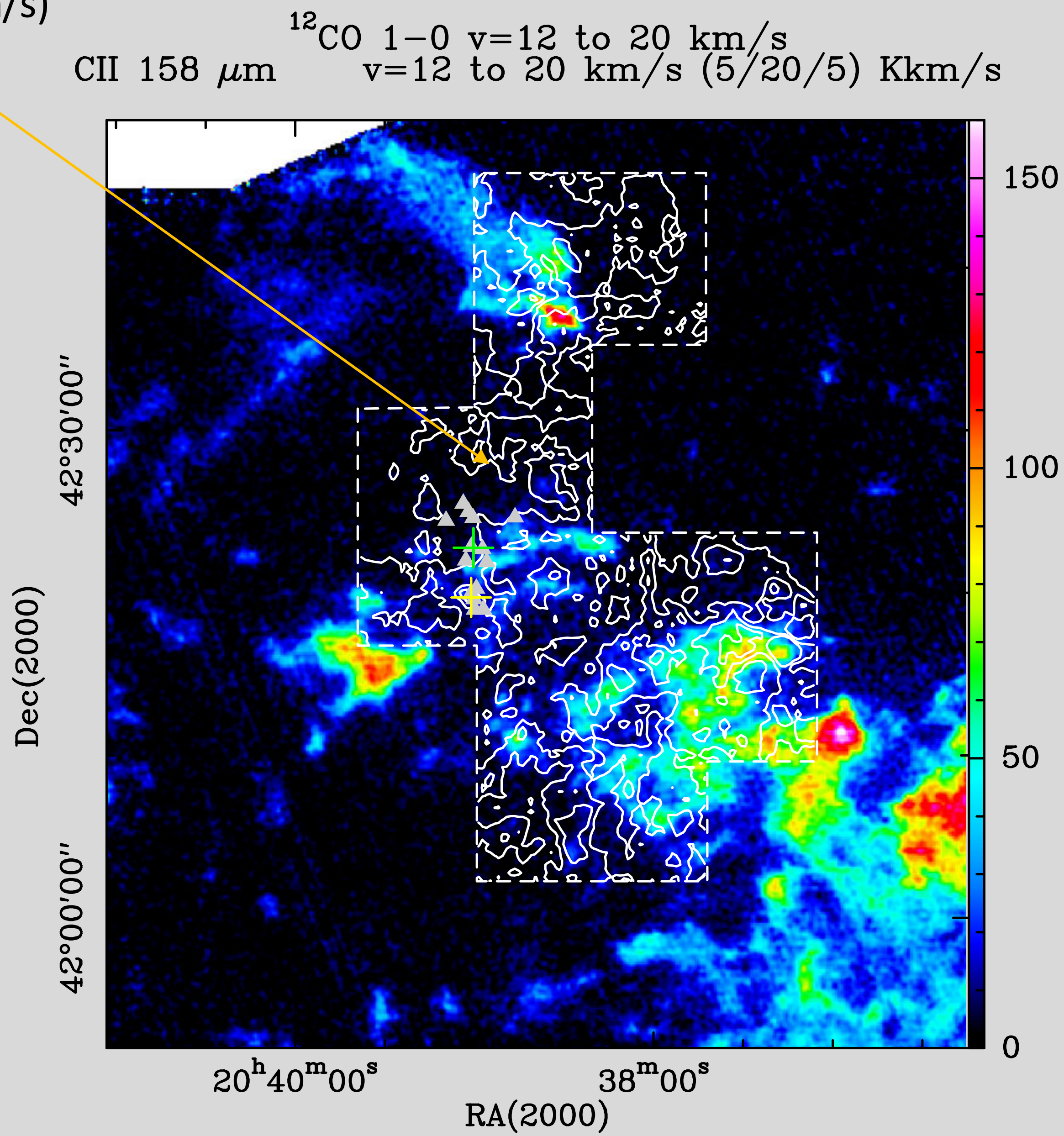
- CO only bright in molecular clouds, dark otherwise (upper limit 4 K km/s @rms 3.5 K km/s).
- CII visible everywhere on a significant level (10 K km/s @rms 1 K km/s).

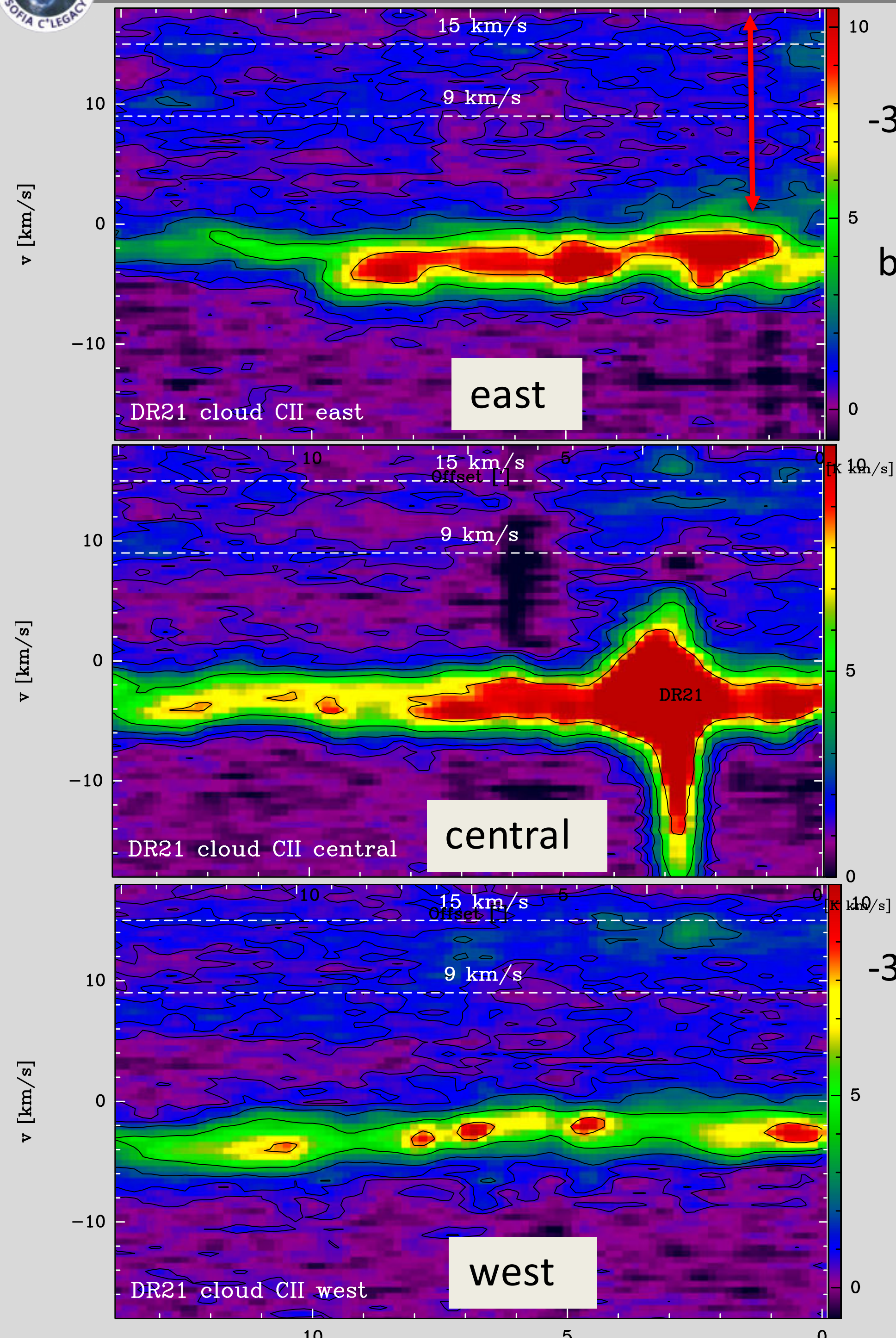




- CO-poor, CII-bright (level 5-10 K km/s)



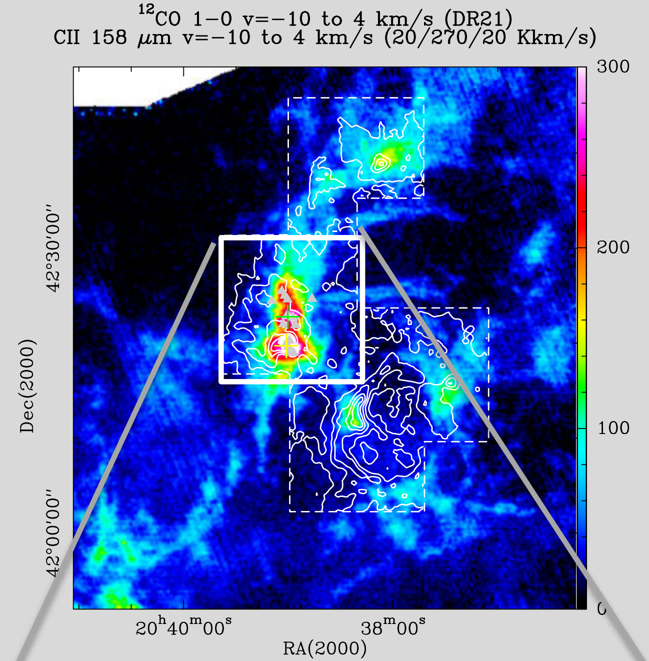


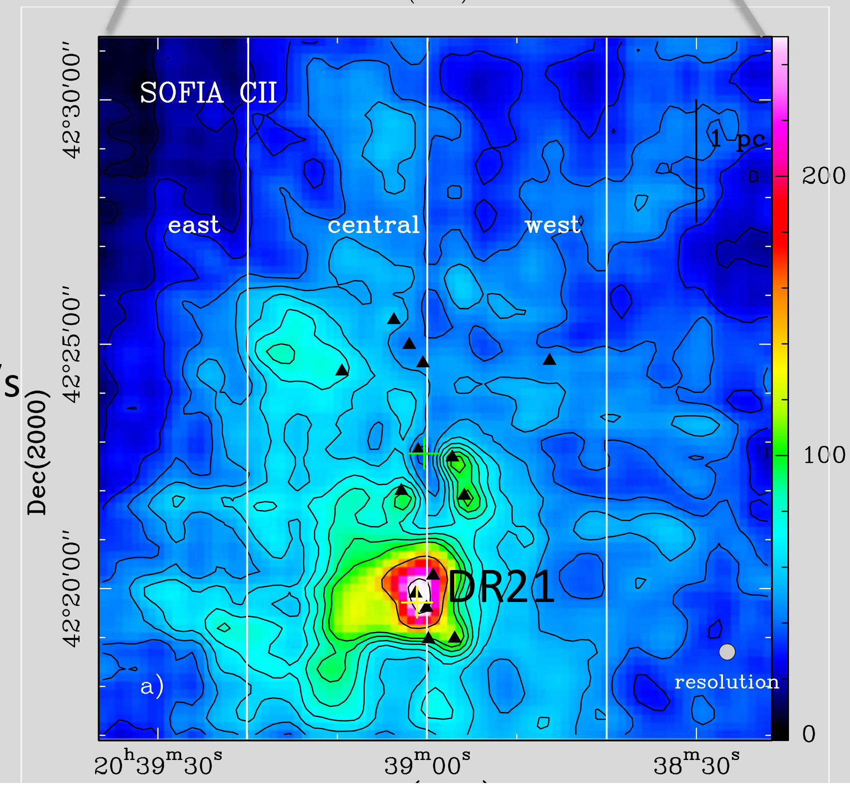


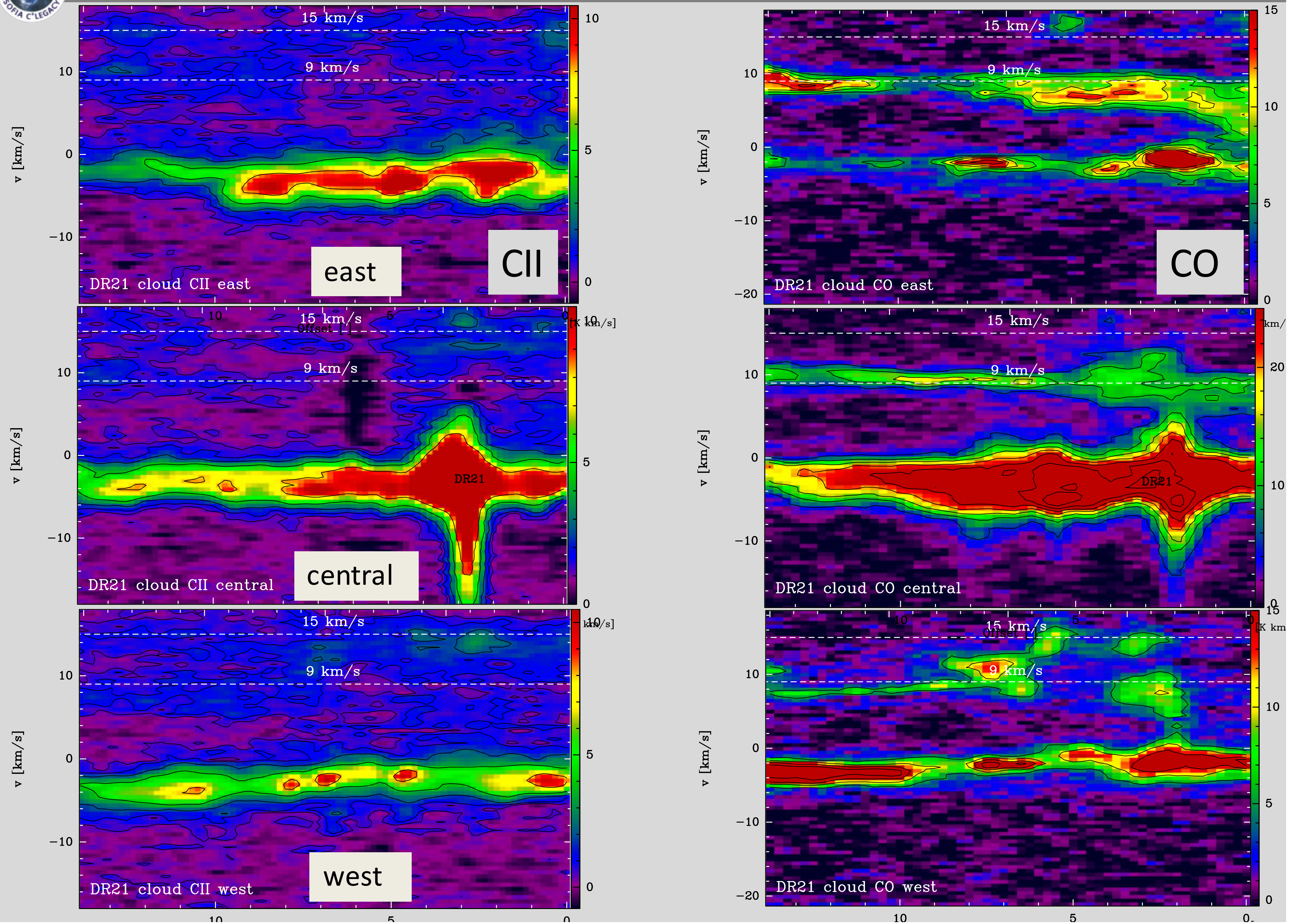
-3 to 18 km/s

bulk emission

-3 to 18 km/s

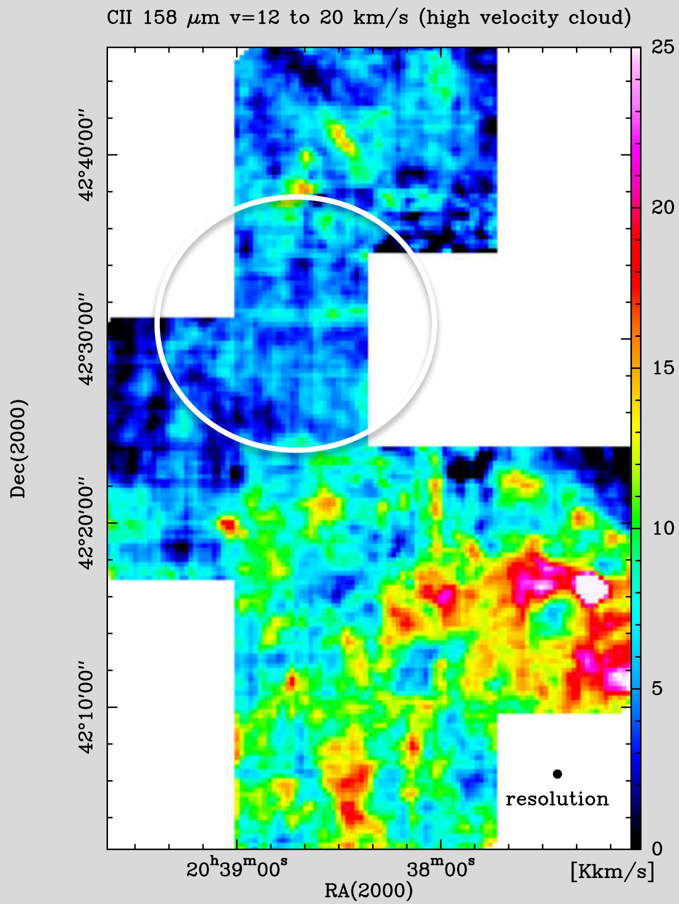


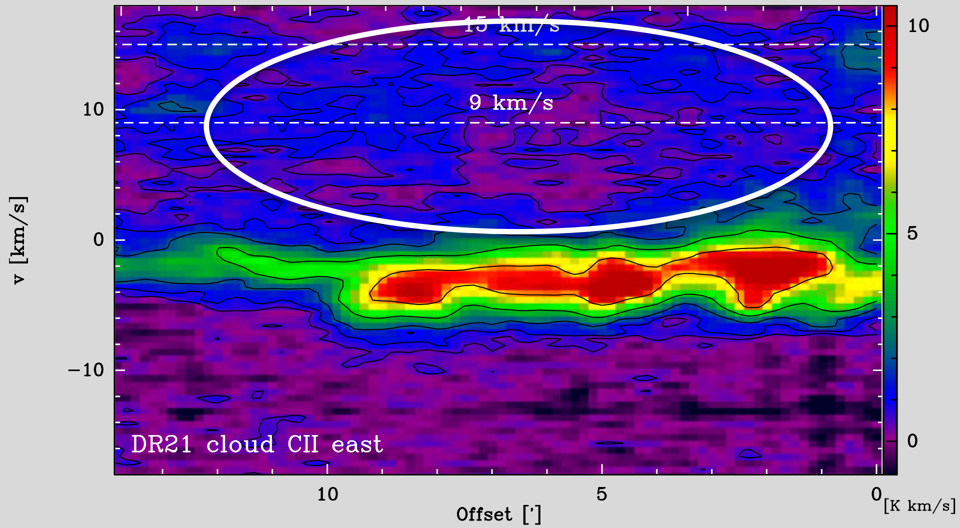




CII
CO
east
central
west
DR21 cloud CII east
DR21 cloud CII central
DR21 cloud CII west
DR21 cloud CO east
DR21 cloud CO central
DR21 cloud CO west
DR21
15 km/s
9 km/s
v [km/s]
Offset [']
[K km/s]

- CO-poor/dark
- CII-bright (5 – 10 K km/s)



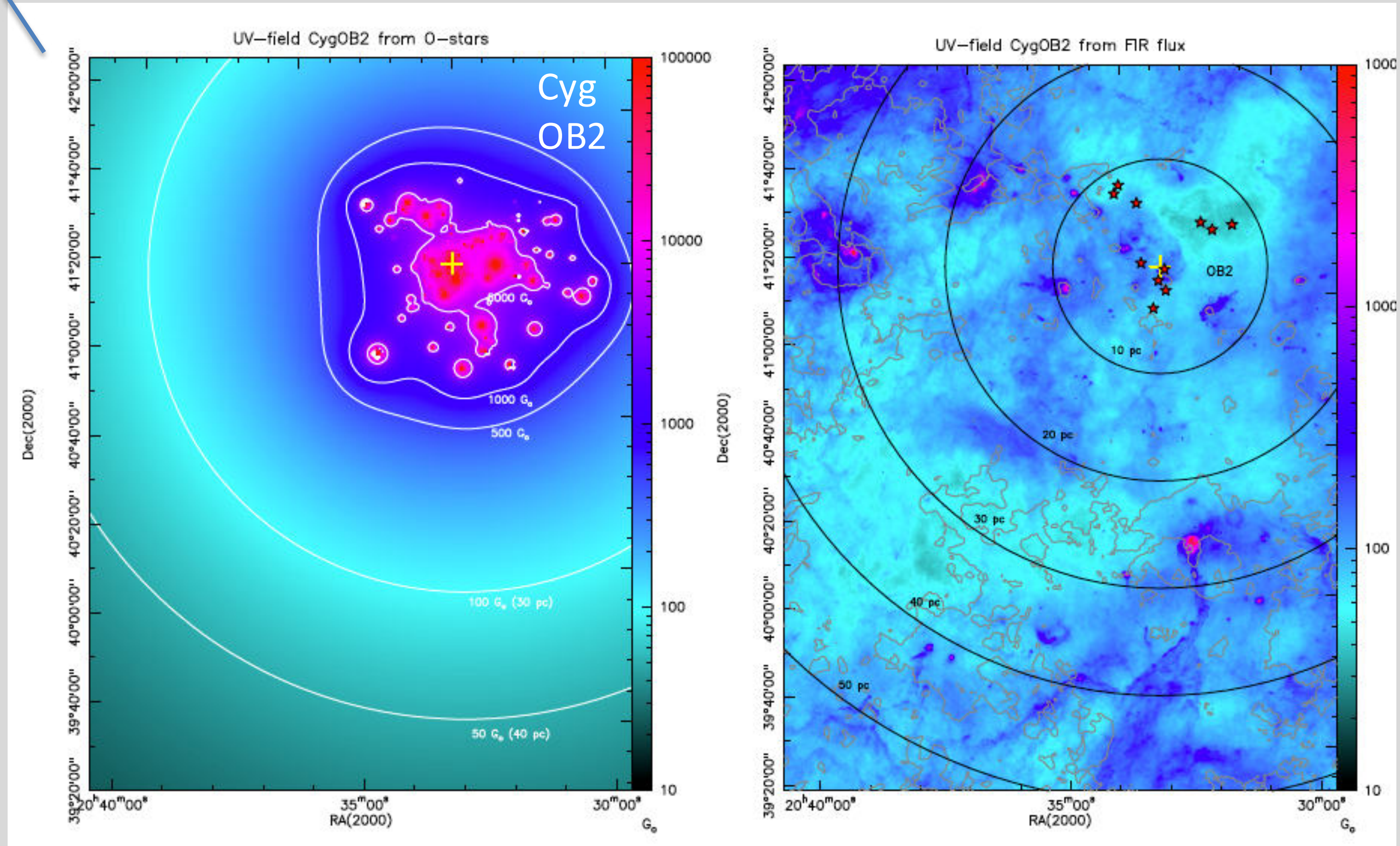


-> need PDR (Photodissociation region) modelling using CII brightness

DR21 ridge

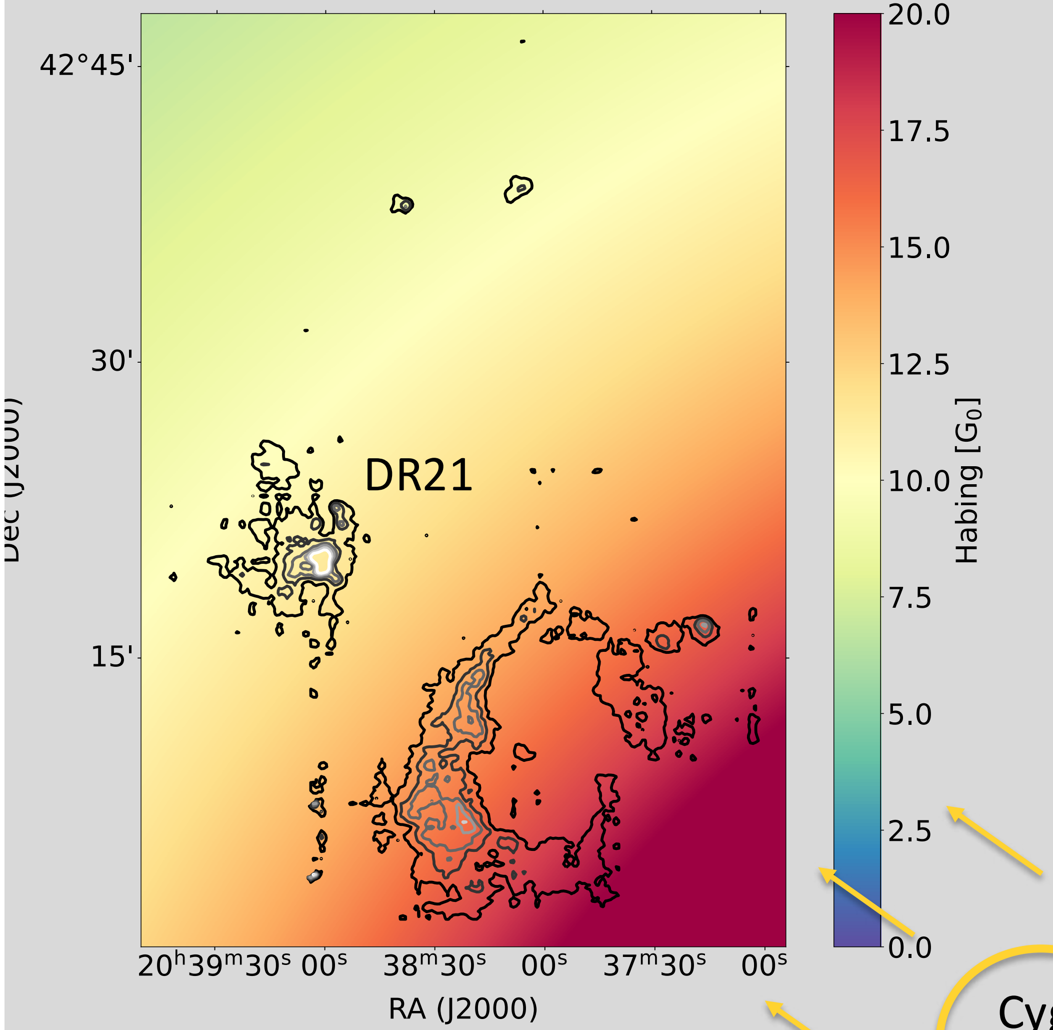
Census of Cyg OB2 stars: **10-30 Go** at the location of the DR21 ridge.

UV field from Herschel fluxes



Schneider et al. 2016a

UV field with contours of CII emission :
~10 G$_o$ at the location of the DR21 ridge



Prepared by S. Kabanovic

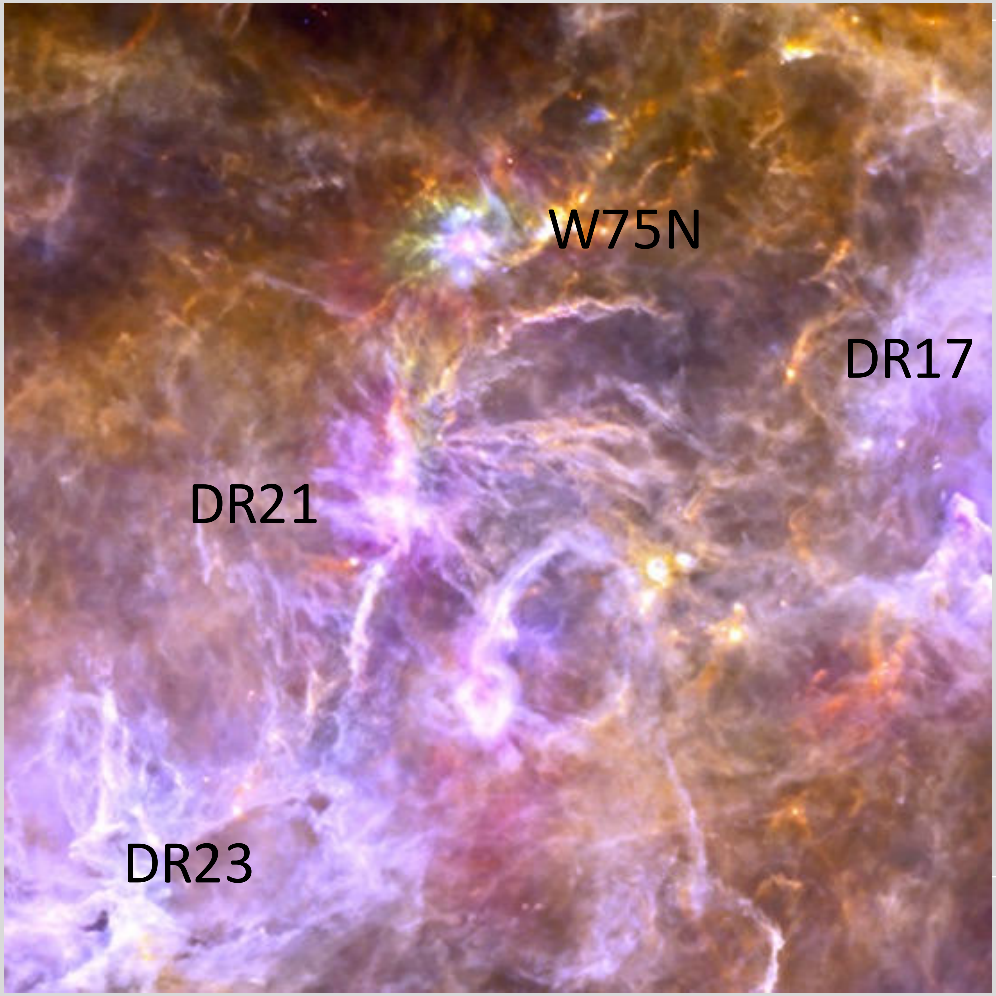
Cyg OB2

<u>Census of stars in Cyg OB2</u> *(Wright et al. 2015):*
169 OB stars with 52 O-type and 3 Wolf-Rayet

From temperature and luminosity of all stars black-body spectrum integrated between 910 and 2066 Å and $1/r^2$ decrease (distance 1.45 kpc)

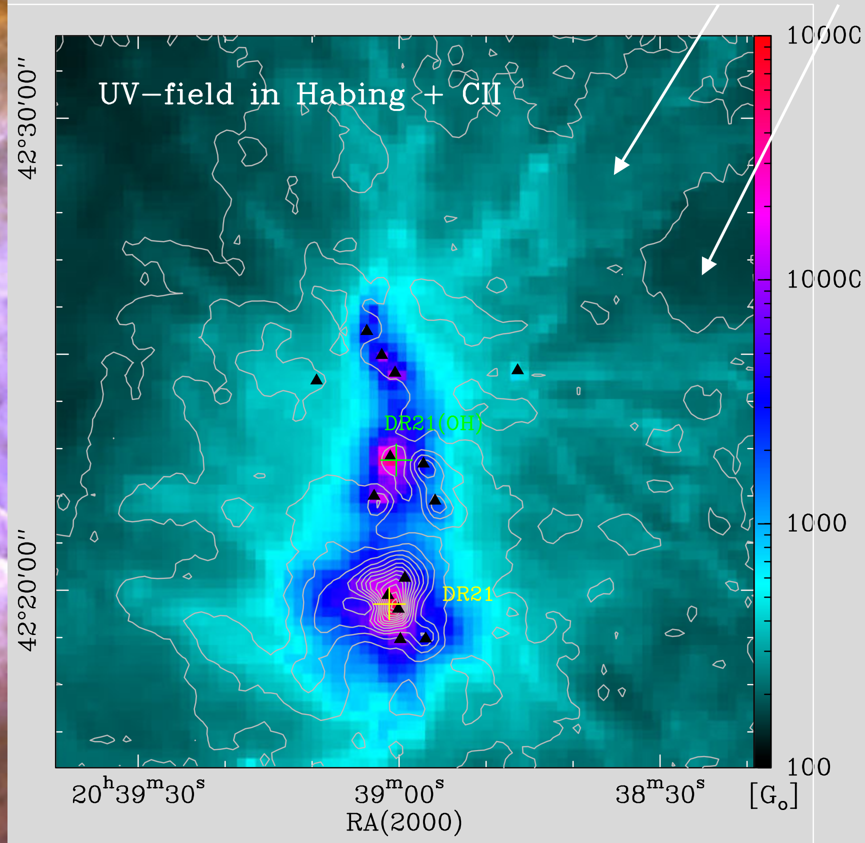
I_UV/I_total = L_UV/L_total

Contribution from stars of DR21, DR23, DR17?
But no O-star identified.



UV field from Herschel fluxes

~100-300 Go

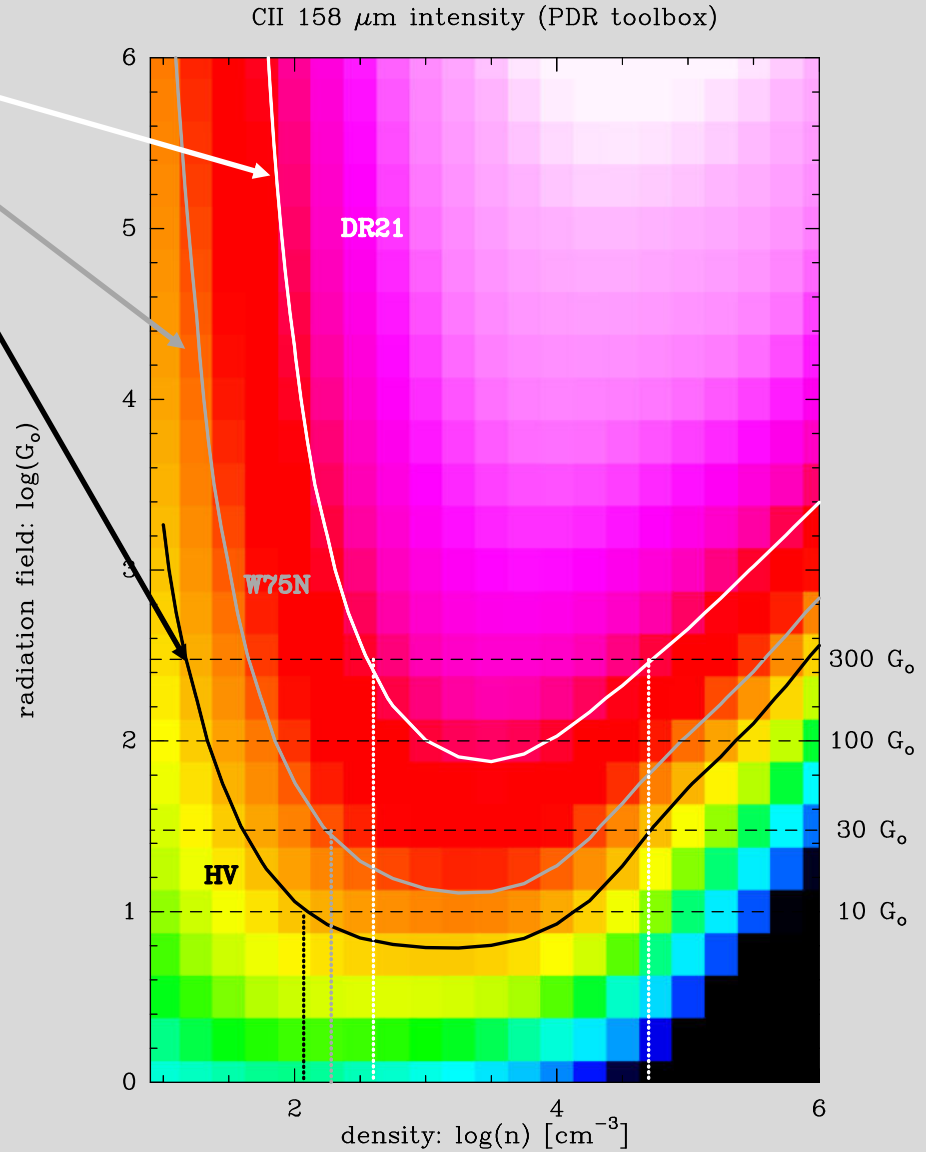


Filaments in DR21 velocity range (outside ridge) I_{CII} ~ 30 K km/s

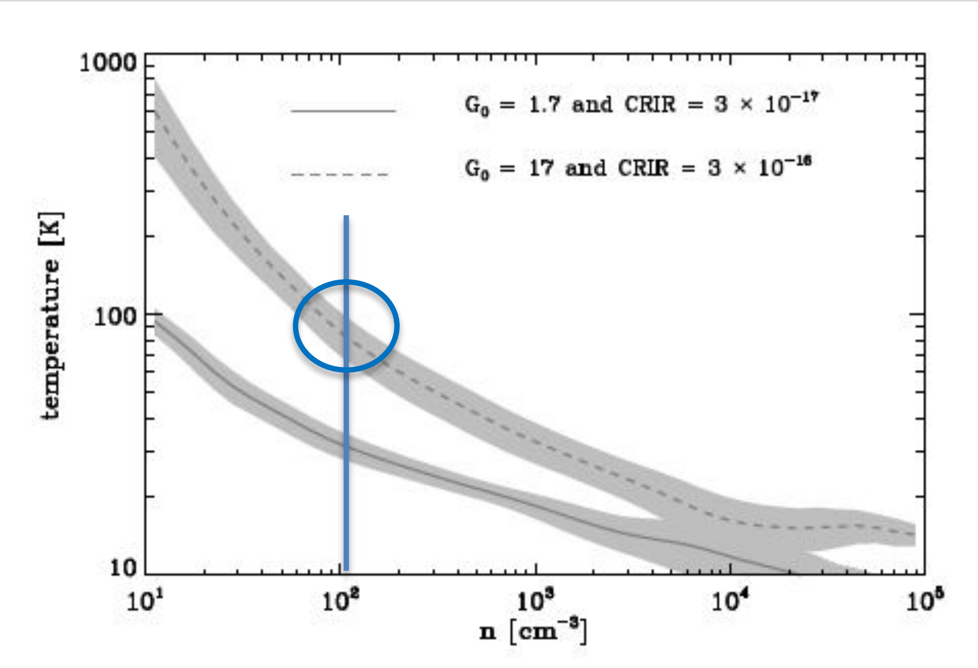
W75 N velocity range I_{CII} ~ 10 K km/s

High-velocity emission I_{CII} ~ 5 K km/s

Velocity range	I_{CII} [K kms^{-1}]	FUV field [G_o]	Density [cm^{-3}]
DR21 (-10 to 4 km s^{-1})	~30	100 - 300	400 – 5 10^4
W75N (4 to 12 km s^{-1})	~10	30	190
High-velocity (12 to 20 km s^{-1})	~5	10	110

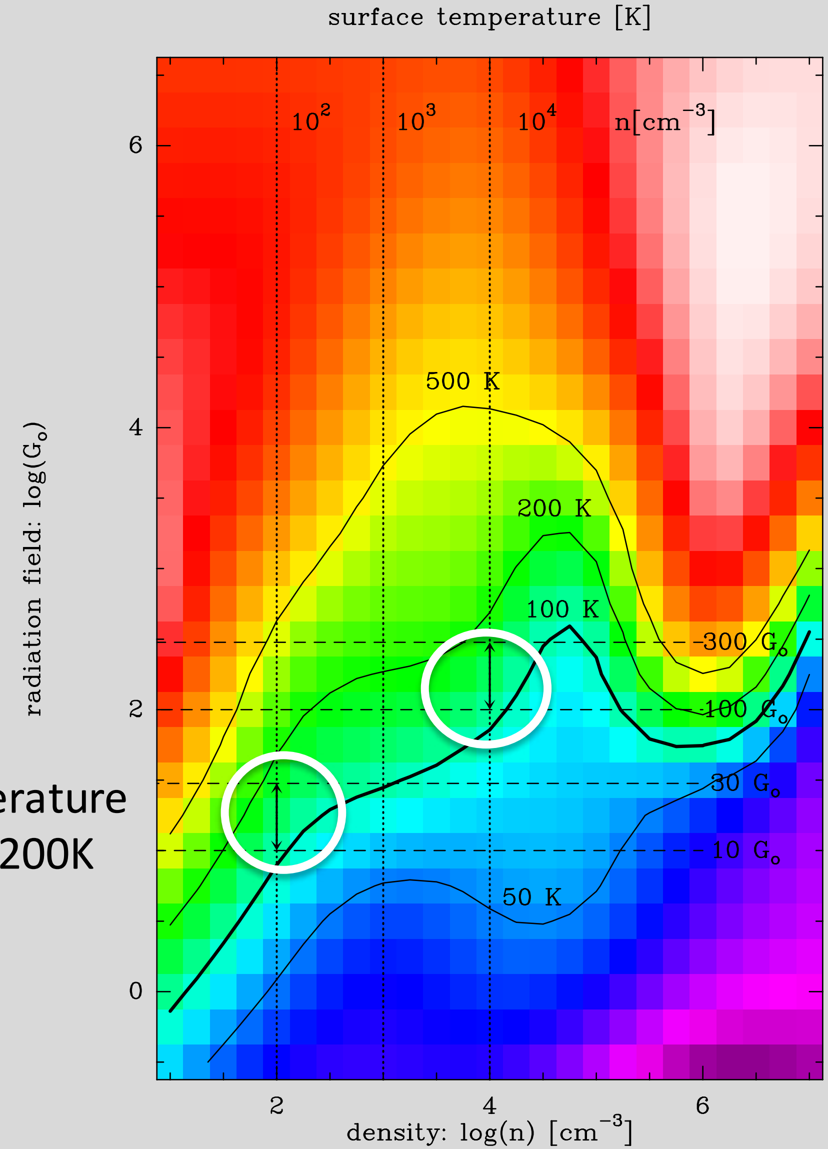


9 km/s and 15 km/s components are consistent with gas at
a **density** of **100 – 200 cm^{-3}** and
a **temperature** of **100 – 200K**



Clark et al. 2019

temperature
100 – 200K



Goldsmith et al. (2012): CII optically thin, sub-thermal excitation

$$N_{\rm CII} = I_{\rm CII} 10^{16}/3.43\times(1+0.5\times\exp(91.25/T_{kin})(1+2.4\times10^{-6}/C_{ul}))$$

$$C_{\rm ul} = n \times R_{ul}$$

collisional de-excitation rate

$$R_{ul}(H^0) = 7.6\times10^{-10}(T^{\rm kin}/100)^{0.14}\ {\rm cm^3\ s^{-1}}$$

collisional de-excitation rate coefficient

C/H = 1.6 10^{-4} (Sofia et al. 2004)

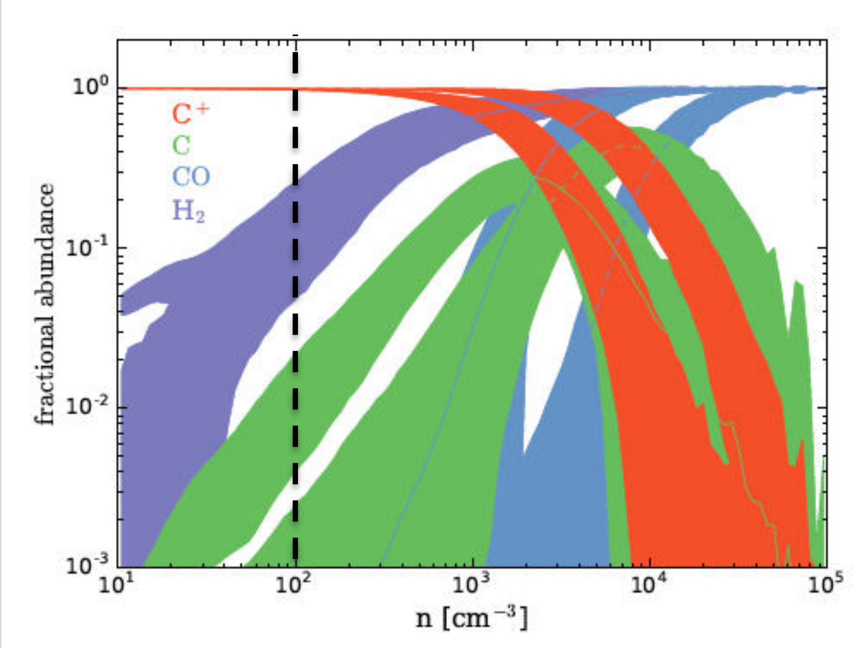
Velocity range	$I_{\rm CII}$ [K $\rm kms^{-1}$]	FUV field [G_o]	Density [$\rm cm^{-3}$]	Temperature [K]	$N_{\rm CII}$ [a] 10^{18} [$\rm cm^{-2}$]	$N(H)$ [b] 10^{21} [$\rm cm^{-2}$]	Mass [c] [$M_\odot$]
DR21 (-10 to 4 km $\rm s^{-1}$)	~30	100 - 300	400 - 5 10^4	100-200	1.06[d], 0.54[e]	6.60[d], 3.38[e]	4550[e]
W75N (4 to 12 km $\rm s^{-1}$)	~10	30	190	200	0.40	2.49	3540
High-velocity (12 to 20 km $\rm s^{-1}$)	~5	10	110	100	0.55	3.46	2440

$$A_{\rm v} = N(H)\times5.348\times10^{-22}$$

$A_{v,obs}$ (9km/s) ~ 1.33
$A_{v,obs}$ (15km/s)~ 1.85

-> $A_{v,eff}$ < 1 consistent with HI/H_2 transition

Observed A_v is a factor of a few ***larger*** than effective A_v used in modelling (Roellig et al. 2007,Seifried et al. 2021).



Clark et al. 2019

Velocity range	I_{CII} [K kms^{-1}]	FUV field [G$_o$]	Density [cm^{-3}]	Temperature [K]	N_{CII}[a] 10^{18} [cm^{-2}]	$N(H)$[b] 10^{21} [cm^{-2}]	Mass[c] [$M_\odot$]
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- Diffuse gas is mostly atomic and contains a significant mass reservoir. (Molecular DR21 ridge contains ~ 12000 M_{sun} *(Schneider et al. 2010, Hennemann et al. 2012)*).

- We observe ***spatially*** and ***kinematically*** extended CII emission in the Cygnus X North region, in particular in **CO-poor regions**.

  -> CII is a good tracer of **CO-dark/poor** gas, confirming findings of e.g. *Pineda et al. (2014)* from the GOTC+ survey: PDRs ~47%, CO-dark H_2 gas (~28%), cold atomic gas (~21%), ionized gas (~4%).

- The CII emitting gas extends over a velocity range of ~***20 km/s***, the gas density is ***100-200*** $\boldsymbol{cm^{-3}}$ at a temperature of ***~100 K***. It is mostly atomic.

- The hydrogen column density (from CII) is low, $\boldsymbol{A_{v,eff} \lesssim 1}$ (HI-H_2 transition).

- No ***head-on collision*** of individual molecular clouds and no gentle, ***low-velocity merging*** of only atomic flows.

- ***High-velocity*** interaction ***('soft collision'***) of atomic flows.

  Small inhomogenities in the diffuse gas can be strongly enhanced and form filaments where CO traces only the ***quiet, molecular*** gas, not revealing the original kinematics in the diffuse gas.

  Similar scenario as presented for the ***Musca/Chamaeleon region*** (Bonne et al. 2020):
  Crossing HI clouds form molecular gas at the convergence of bended magnetic fields behind the shock front in HI.

- Unclear what drives the fast atomic flows.
  v < 10 km/s is approximately the sound speed in turbulent HI gas in the WNM,
  v > 20 km/s require dynamical processes on galactic scales, such as streaming motions due to spiral arm waves.

- These flows can build up ***OB clusters*** (Dobbs et al. 2020).

- A detailed study (CO, CII) of the DR21 ridge is in preparation (Lars Bonne et al.), including discussing the magnetic field which is important for the star-formation history of the region.
  (Magnetic fields are measured with HAWK+ (Pillai et al.)).

- More **FEEDBACK** sources will be investigated in CII and CO (but need extended CII maps, not all is done yet).