Heterodyne spectroscopy pf the interstellar medium : from millimeter to far infrared wavelengths

Maryvonne Gerin

Questions for today and for the future

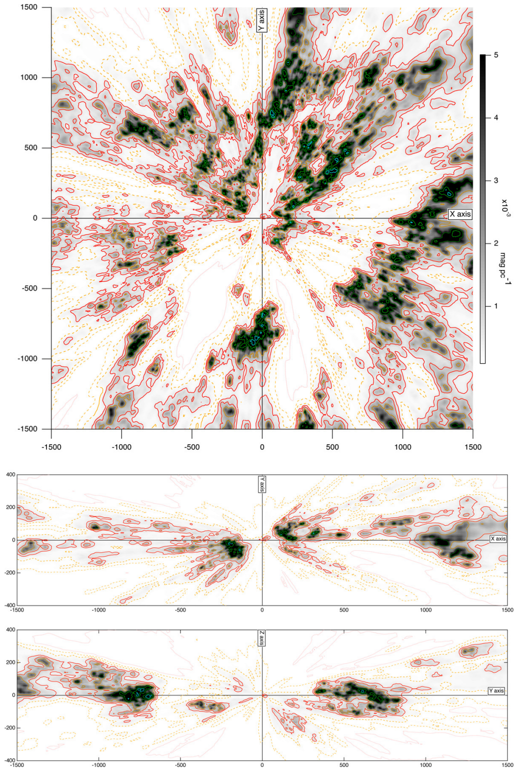
- How to get an accurate characterization of the gas ?
  - structure : density and column density distribution
  - kinematics : velocity field, turbulence properties, shocks
  - physical parameters : electron fraction, CRIR, UV radiation field, magnetic field
  - composition : elemental abundances, depletions, atomic and molecular abundances

➔ Accessible through detailed analysis and modeling of atomic and molecular spectral lines including ions

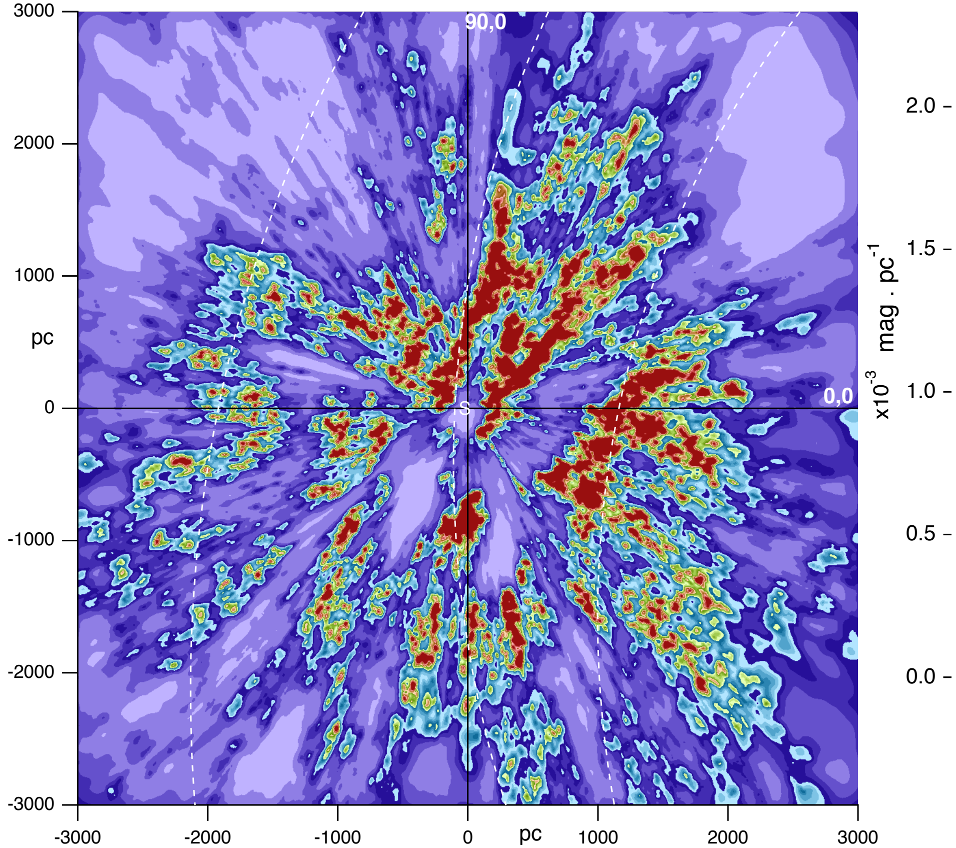
➔ Broad spectral coverage

➔ Combination of data science and physics-based approaches

Gas and dust structures : inversion of the extinction

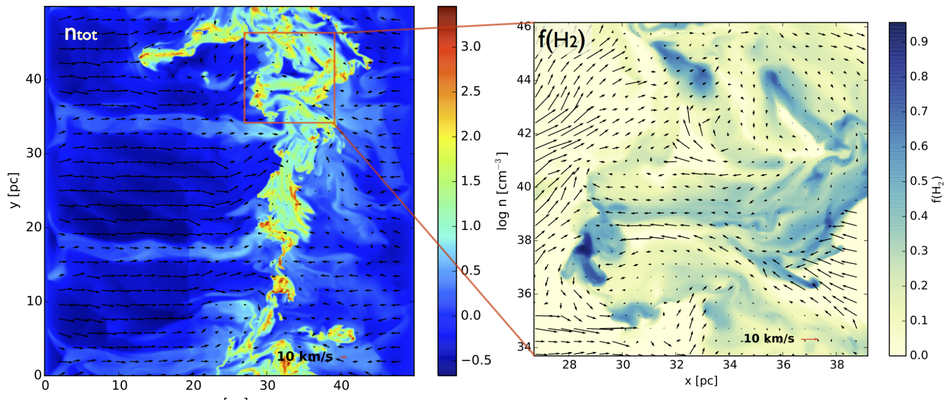


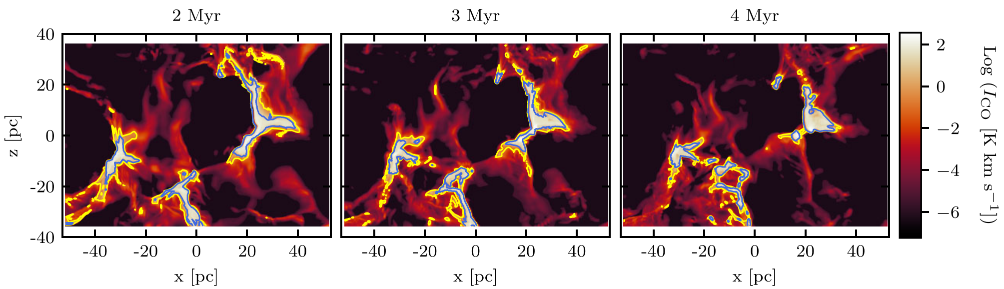
- Large stellar surveys including GAIA
- known clouds are identified
- Dust and gas clouds separated by large low density bubbles with little dust : 3 phase model ?
- Limited spatial resolution
- Less accurate at large distances



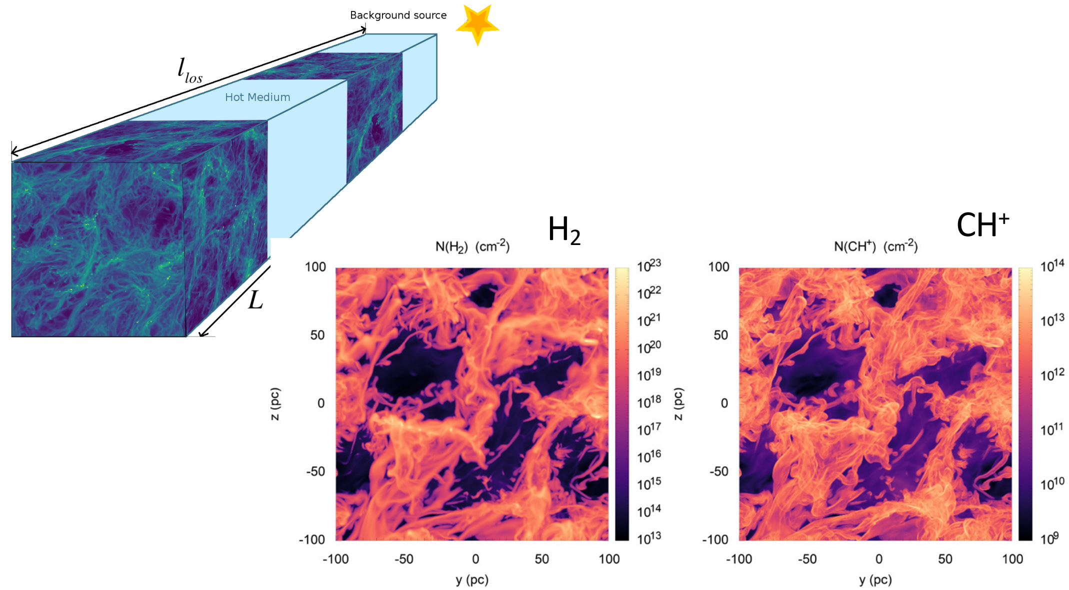
Vergely+2022

Numerical simulations & models





Validivia+2017, Bellomi+2021,Borchert+2022,Godard+2023



High resolution MHD + heating/cooling + UV radiation propagation + calculation of synthetic observations

Chemistry : on the flight (H, H_2 , CO ..) and/or post processing

→ Good account of the complex structure along the line of sight

→ Simplified physics and chemistry & non steady state effects , important role of the numerical resolution

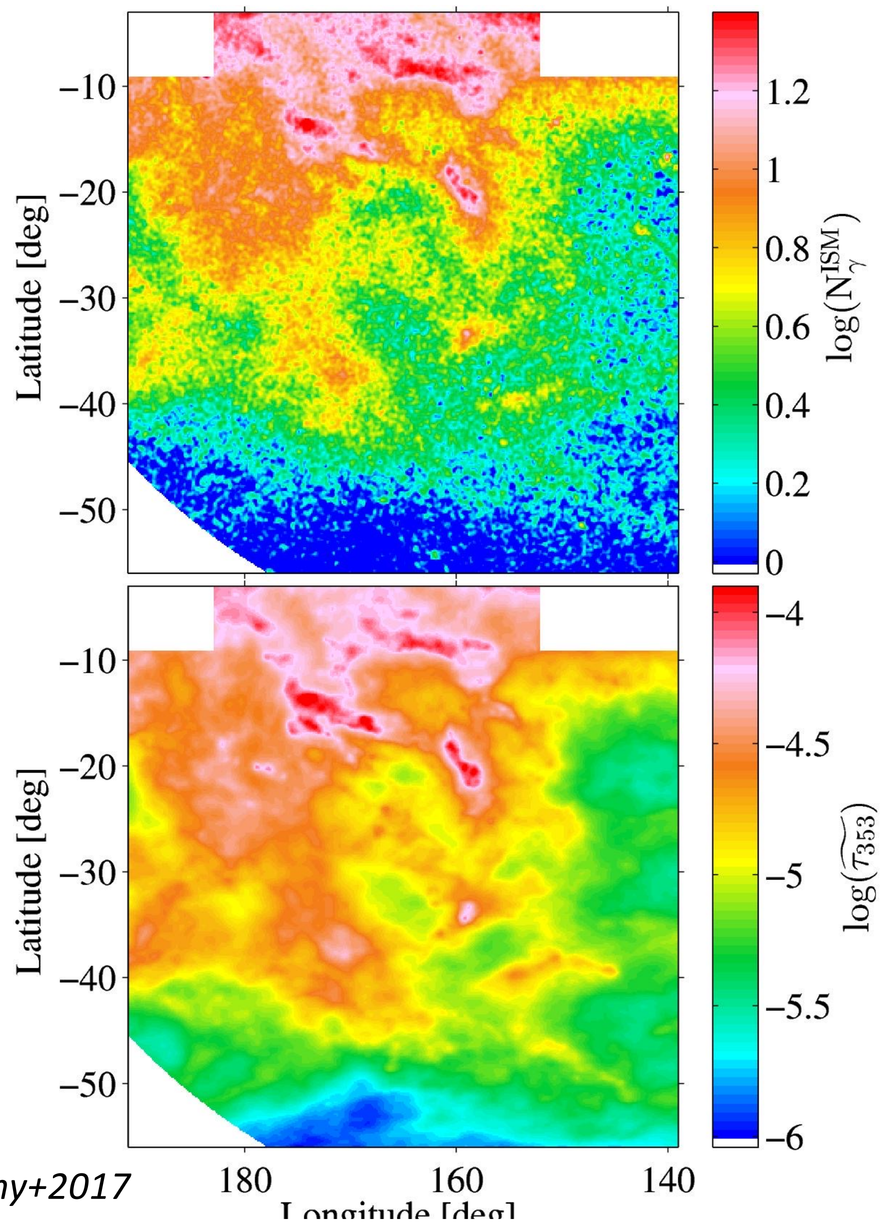
→ Comparisons using various species - CO may not be the best case → Use C+, O, hydrides ?

Probing the ISM Phases with observations

- Information on all phases is necessary for the full picture
- Structure, dynamics and relative motions : kinematic information is essential
- Total gas
  - From dust : far IR and submm emission, dust extinction
  - from gamma ray (interaction of cosmic rays with the matter)
  - Full Milky Way maps available as well as nearby galaxies

  → No kinematics

  →Dust properties change with the environment : uncertainty in the gas/dust ratio



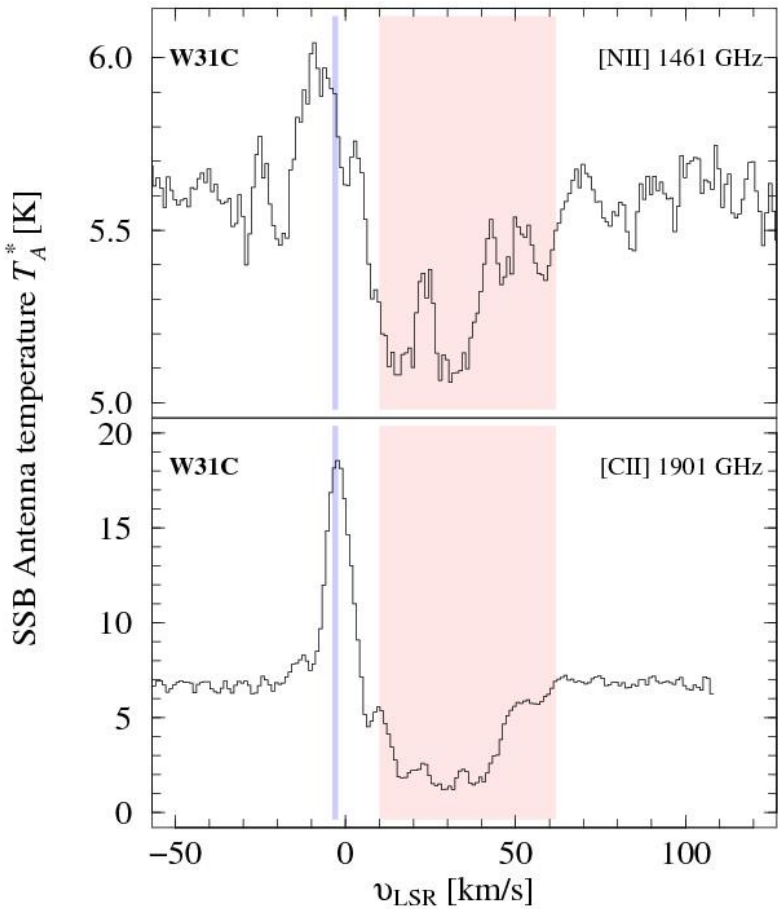
Remy+2017

Probing the ISM phases with observations : ionized gas

- Diffuse Warm Ionized gas :
  - Hydrogen Recombination lines Hα
  - Far infrared fine structure lines including [NII]

→Absorption along the line of sight consistent with the expected WIM properties (N ~ 1.5 10^{17} cm^{-2}, n ~0.1 – 0.3 cm^{-3}, volume filling factor ~0.3)

→ Waiting for the ASTHROS balloon ?

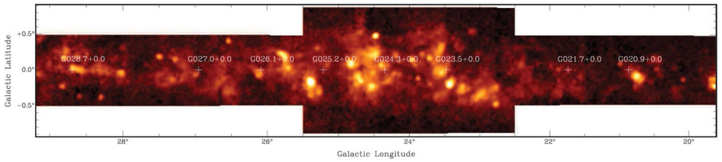


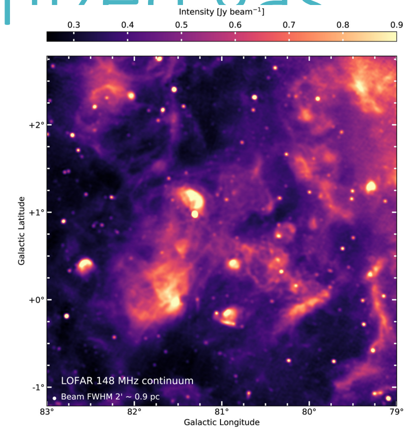
Persson+2014;Langer+2021

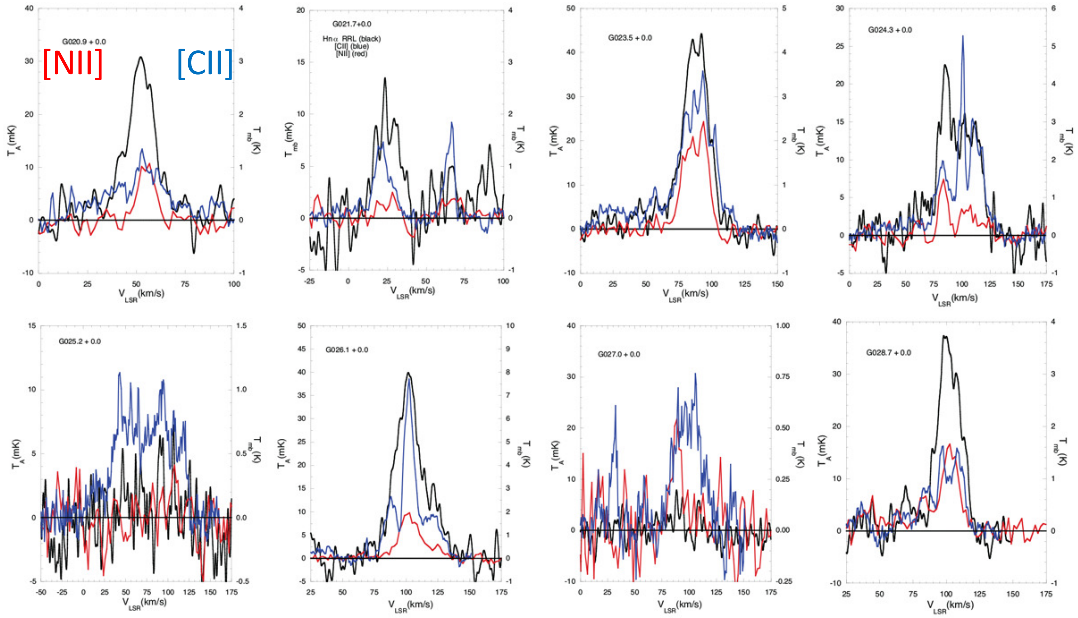
Probing the ISM phases with observations : ionized gas

- Dense and warm Ionized gas :
  - Far infrared fine structure lines including [NII] in emission
  - Electron temperature (3500-9000 K)
  - High electron density (10-30 cm^{-3})
  - High thermal pressure (> 10^4 Kcm^{-3})

→ related to ionized filamentary structures (photo evaporation) ?



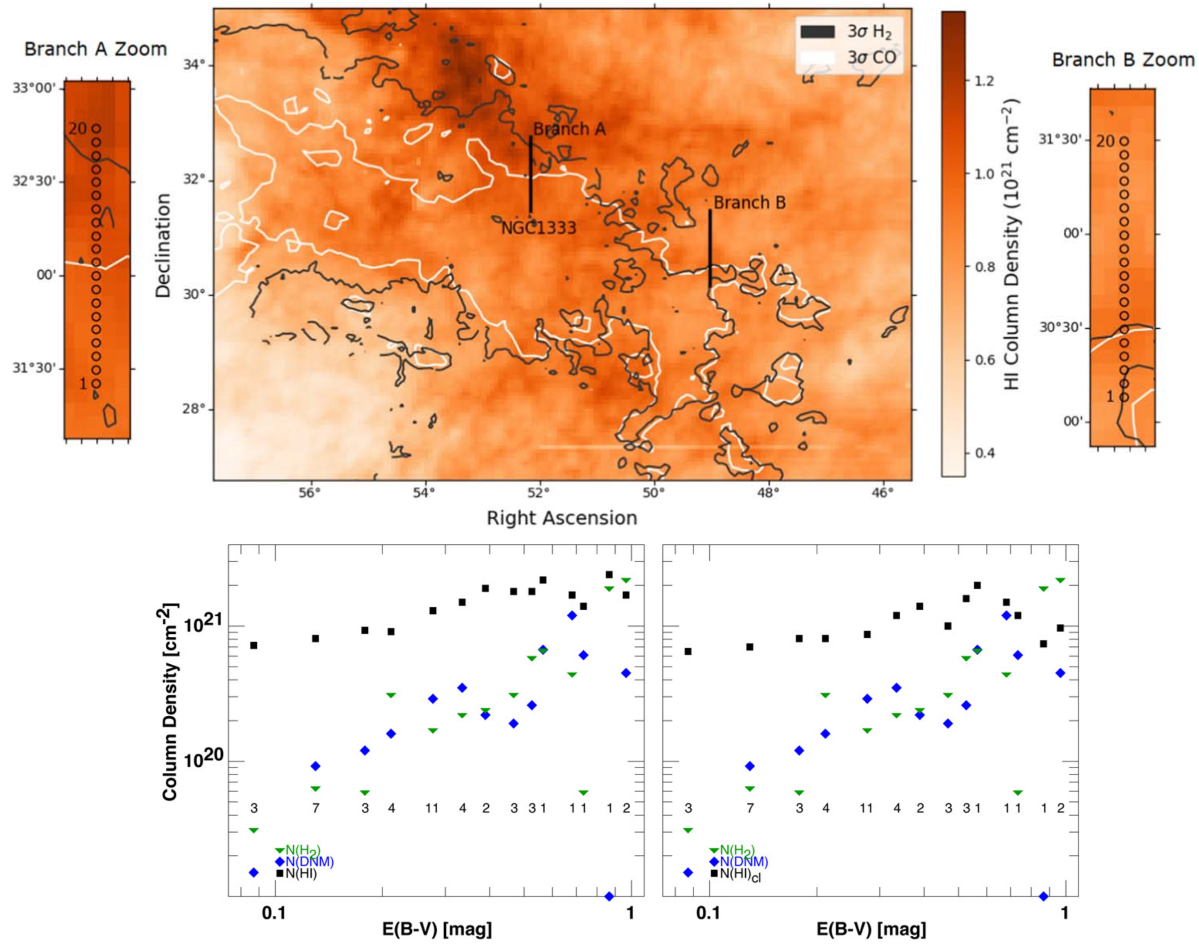




Langer+2021,Emig+2023

Probing the ISM Phases with observations : atomic H

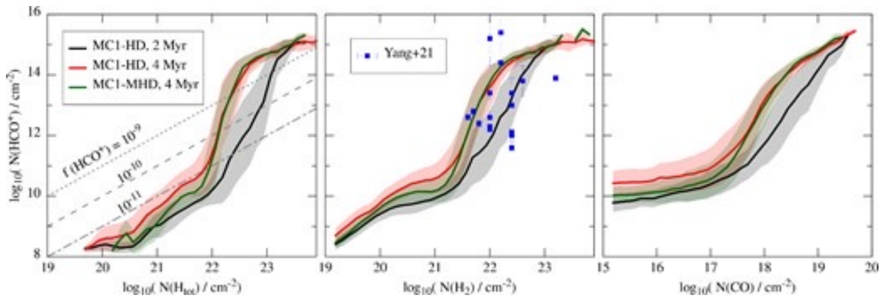
- Neutral Atomic gas
  - from HI emission and absorption surveys
  - Correction for optical depth
  - Separation of cold (absorption) and warm (broad emission lines) HI
  - HI dominates in the cloud “envelope” but does not trace the dense structures
  - Association with [CII] absorption & emission for the ”cold” HI

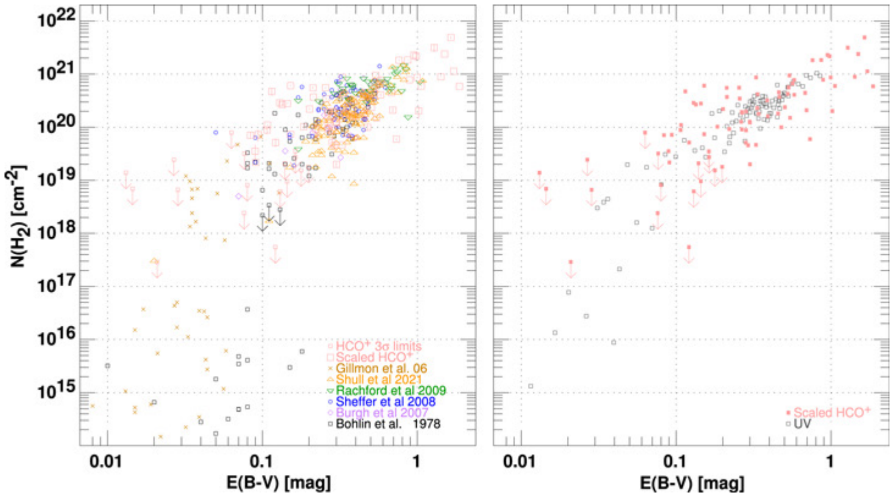


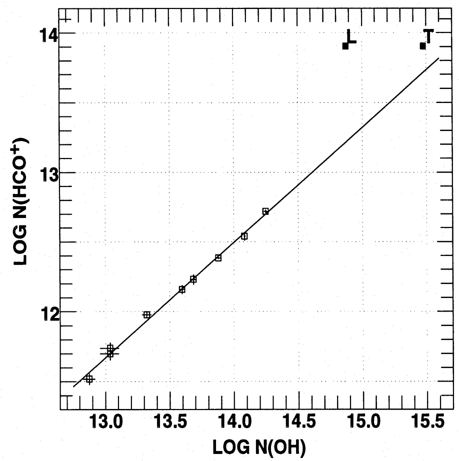
Hall+2020; Liszt+2023

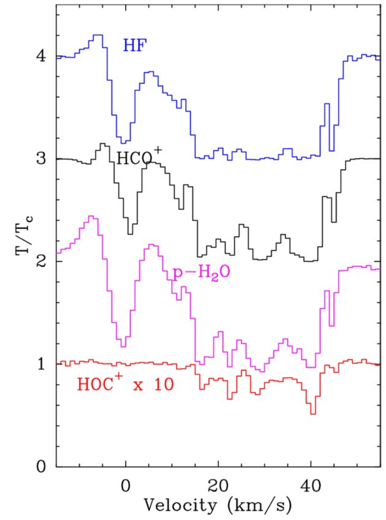
Probing the ISM phases from observations : molecular gas

- Hydrides as proxy for H_2 : HF, CH , OH
- HCO^+ absorption can be used as a proxy for H_2 ($[HCO^+/H_2] = 3x10^{-9}$ within less than a factor of 2)
- Calibration with hydrides (CH, HF, OH and H_2O)
- Same threshold for HCO^+ or H_2 detection and same variation with E(B-V)
- Very weak emission → low to moderate densities : 100 – 500 cm^{-3}
- Challenge for chemical models





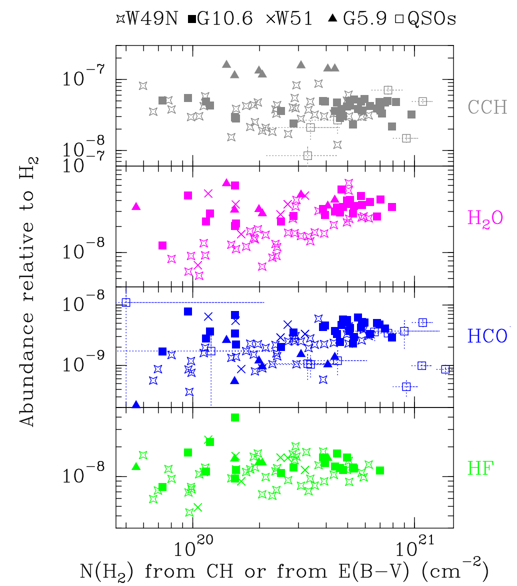




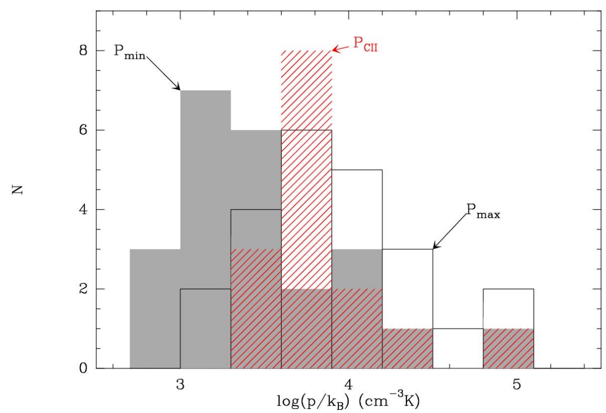
Lucas & Liszt 1996,
Liszt+2023, Gerin+2019, Panessa+2023

Measuring diffuse & translucent molecular gas

Molecule	Abundance	Uncertainty dex	Comment	$N(H_2)/\int \tau dv$ $cm^{-2}/km\ s^{-1}$
HCO^+	3.1×10^{-9}	0.21	Using [CH] = 3.6×10^{-8} and E(B-V)[e]	4.0×10^{20}
HOC^+	4.6×10^{-11}	0.21	From $[HOC^+]/[HCO^+]$	5.2×10^{22}
CF^+	1.7×10^{-10}	0.30	From $[CF^+]/[HCO^+]$	9.0×10^{22}
C_3H^+	7.5×10^{-11}	0.30	From $[C_3H^+]/[HCO^+]$	2.0×10^{23}
HF	1.2×10^{-8}	0.14	Using [CH] = 3.6×10^{-8}[e]	2.0×10^{20}
H_2O[a]	2.7×10^{-8}	0.20	Using [CH] = 3.6×10^{-8}[e]	3.4×10^{20}
CCH	4.4×10^{-8}	0.15	Using [CH] = 3.6×10^{-8}[e]	1.5×10^{21}
CH[b]	3.6×10^{-8}	0.21	Sheffer et al. (2008)	1.0×10^{21}
CH[c]	3.6×10^{-8}	0.21	Sheffer et al. (2008)	9.7×10^{20}
OH[d]	1.0×10^{-7}	0.1	Weselak et al. (2010)	2.5×10^{20}

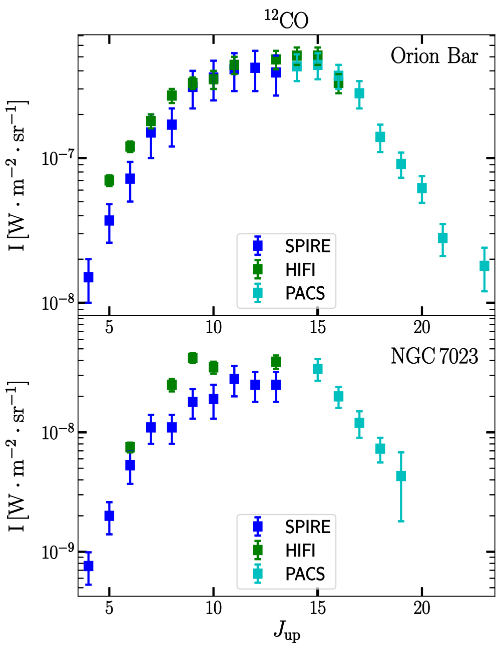


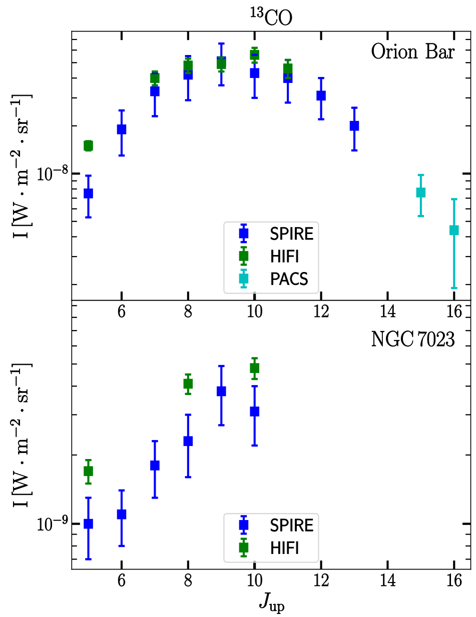
- Range of tracers with different sensitivities
- Hydrides lines in the far infrared are the most sensitive and have a relatively well understood chemistry
- Transition to translucent and molecular gas : CO isotopologues
- Specific submm/far infrared lines : [CI] (gas pressure), HD

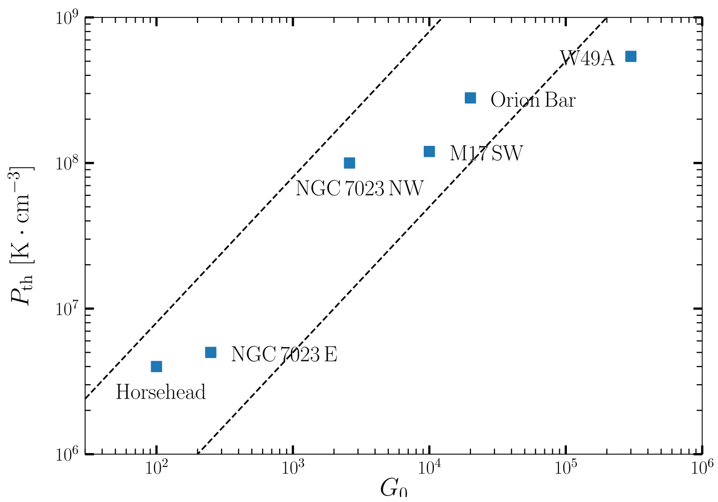


Gerin+2015,2019

Molecular gas excitation : the CO ladder







- Dense PDRs : Orion Bar and NGC 7023. Detection of CO emission up to J =18 !

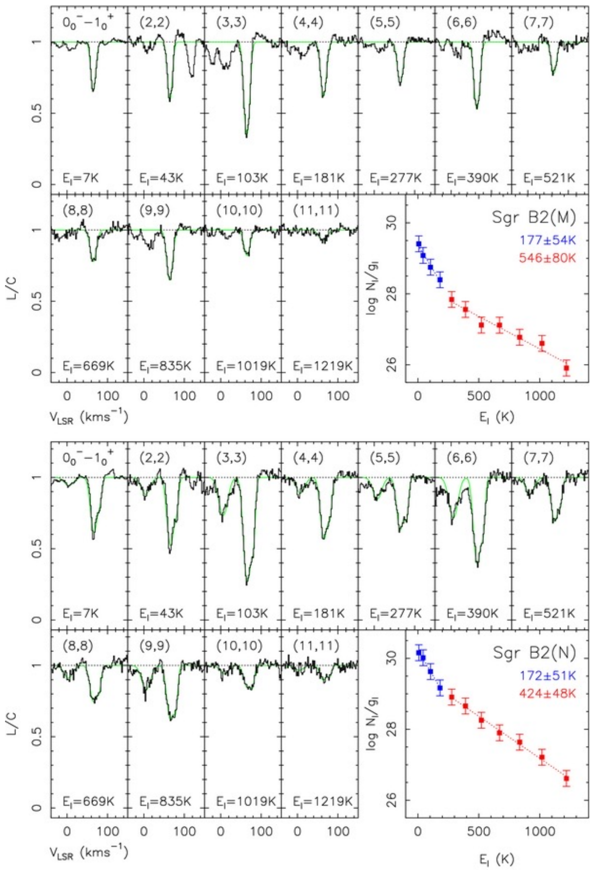
→ Good characterization of the dense gas pressure

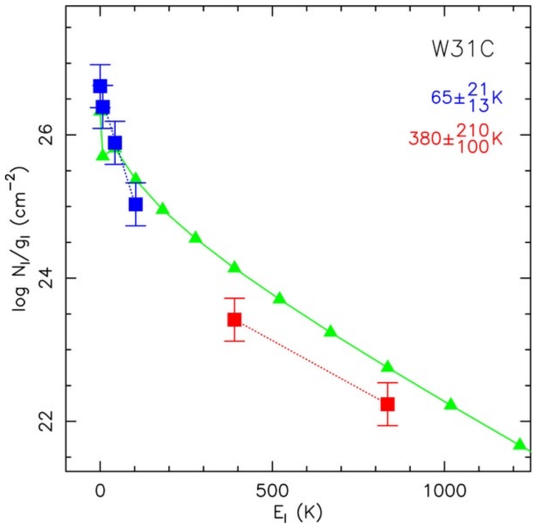
→ Relation between Pth and G0 : feedback

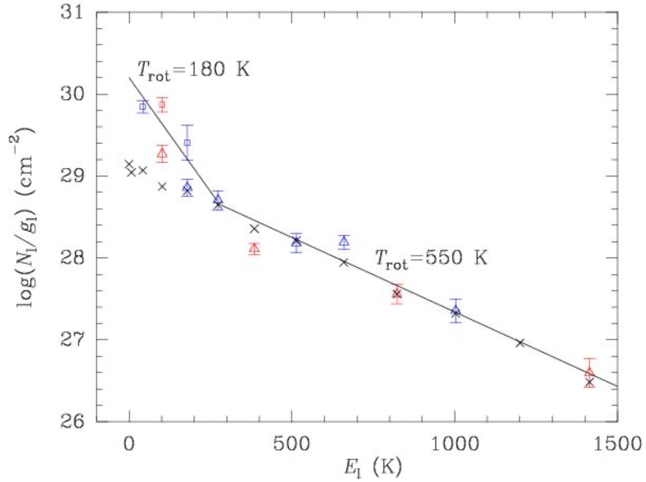
- Implication for CO emission in active and high z galaxies : small regions can contribute a large fraction of the flux

Joblin+2018

Molecular gas excitation : metastable H_3O^+ levels







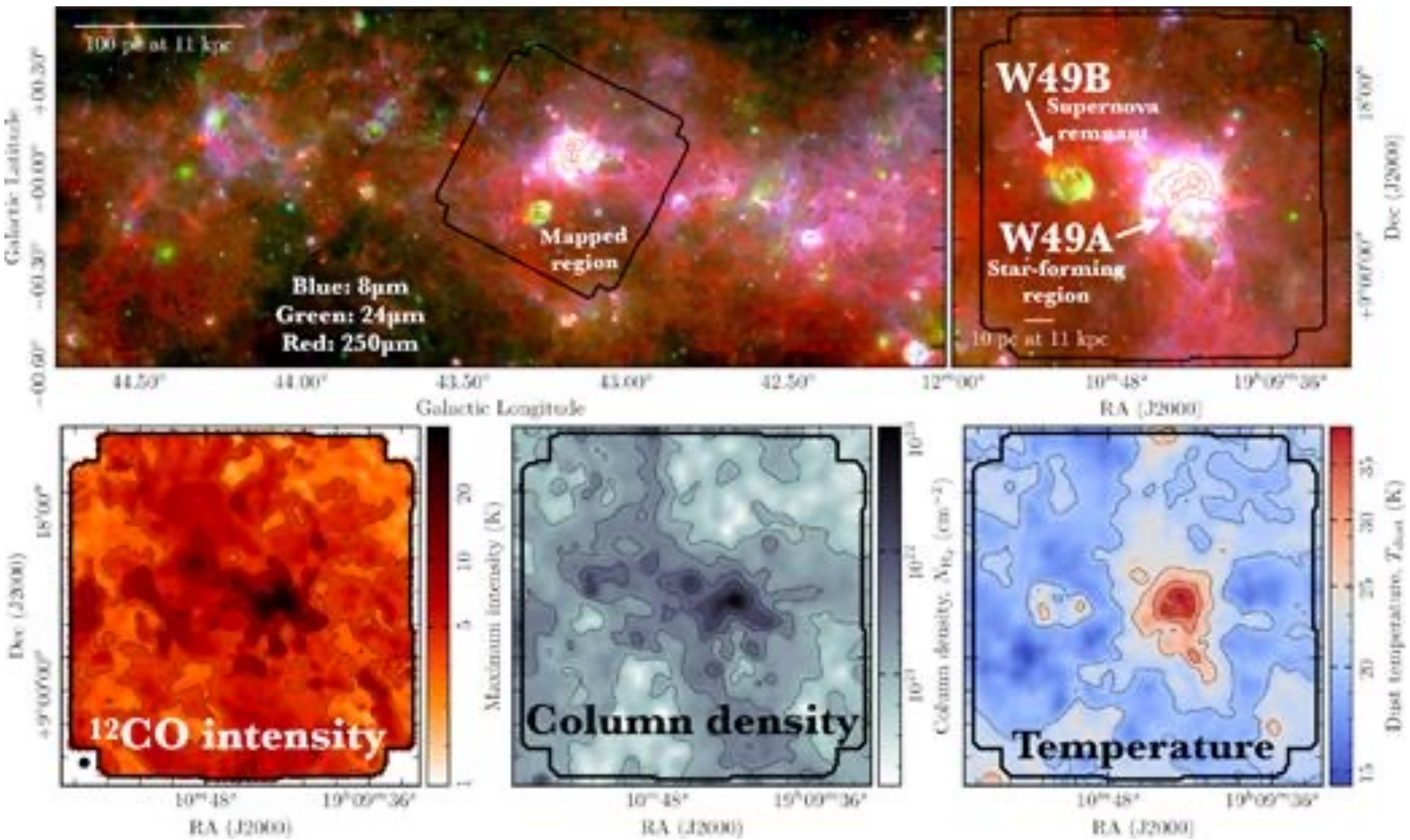
- Excitation consistent with formation pumping

→Abundance and level population depend on the cosmic ray ionization rate

→ Same phenomenon in active compact galaxies like Arp220, up to high redshifts

Lis+2014, Gonzalez-Alfonso+ 2013

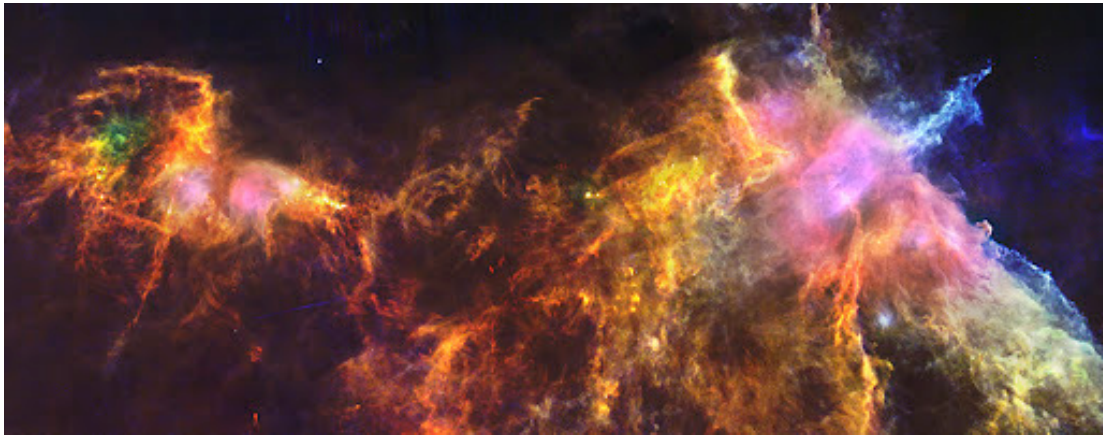
The benefit of large scale maps



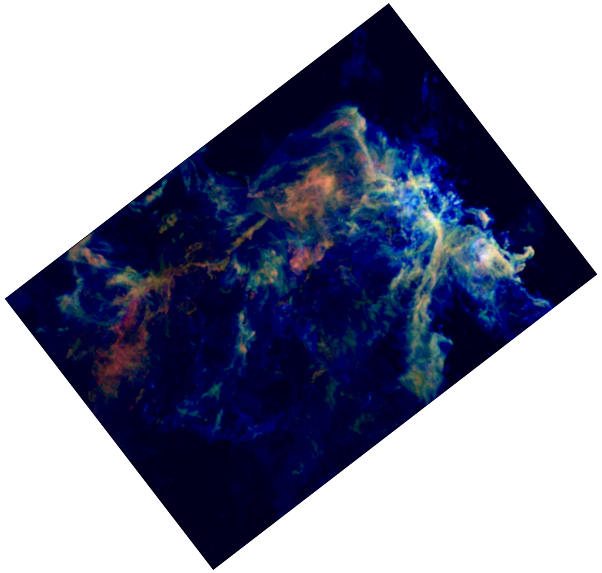
Separation of the material associated to the distant star forming region W49N and the gas along the line of sight

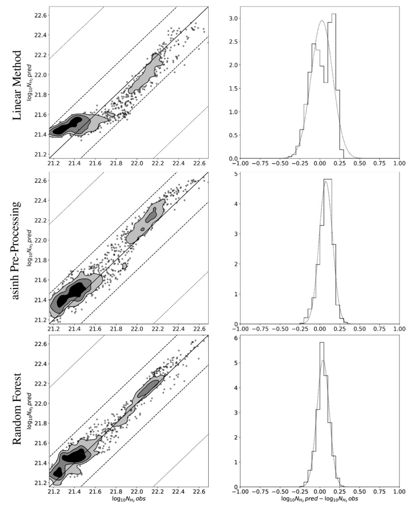
LEGO, W49N Barnes+2020

The benefit of large scale maps



Orion B Herschel vs IRAM-30m

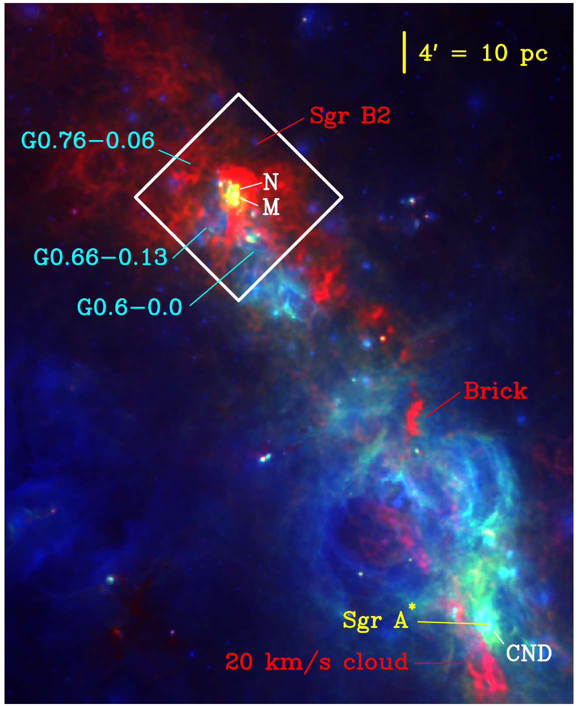


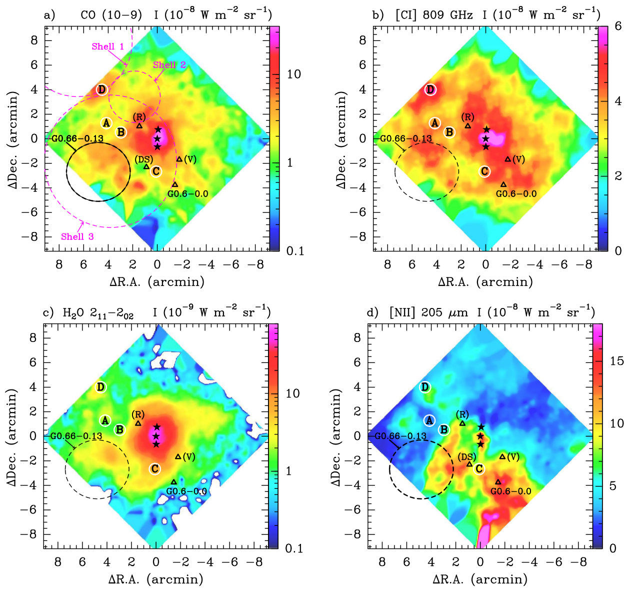


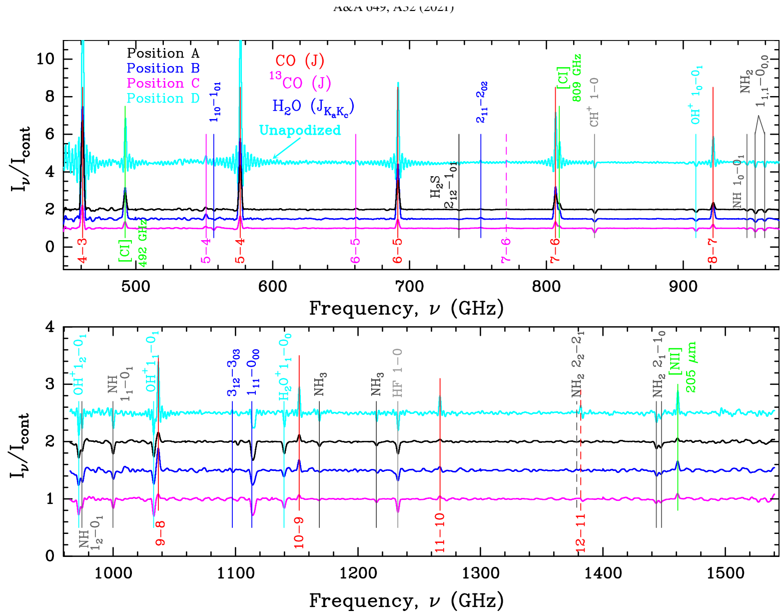
Gratier+2021

- Large dynamical range of spatial scales
- Large variety of environments
- Relation between star forming regions and their environment
- Spectral line maps are smaller than photometry but bring complementary information

The benefic of large scale maps





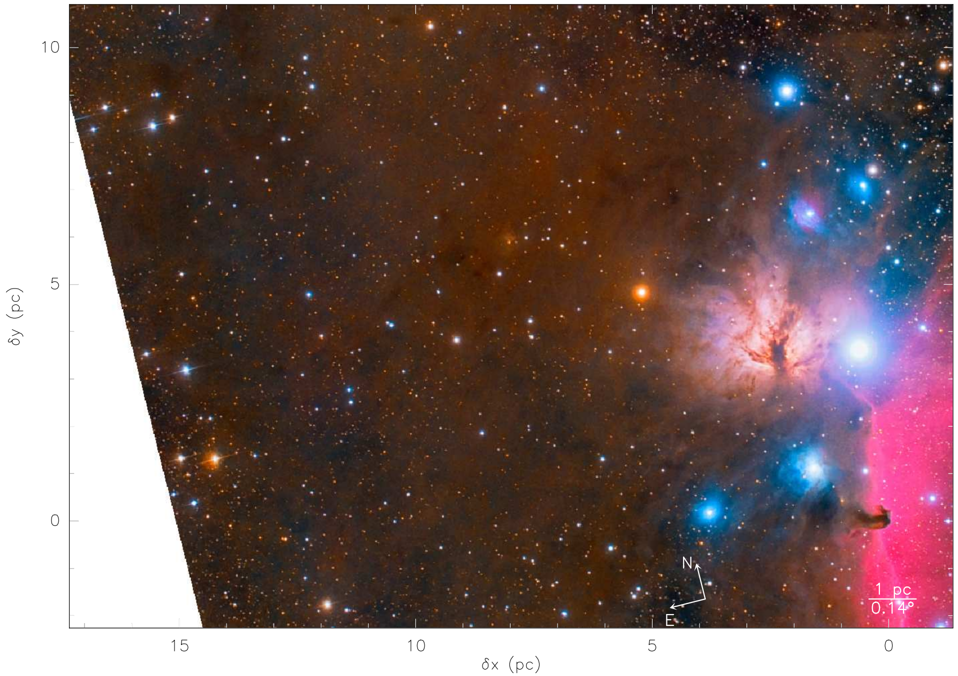


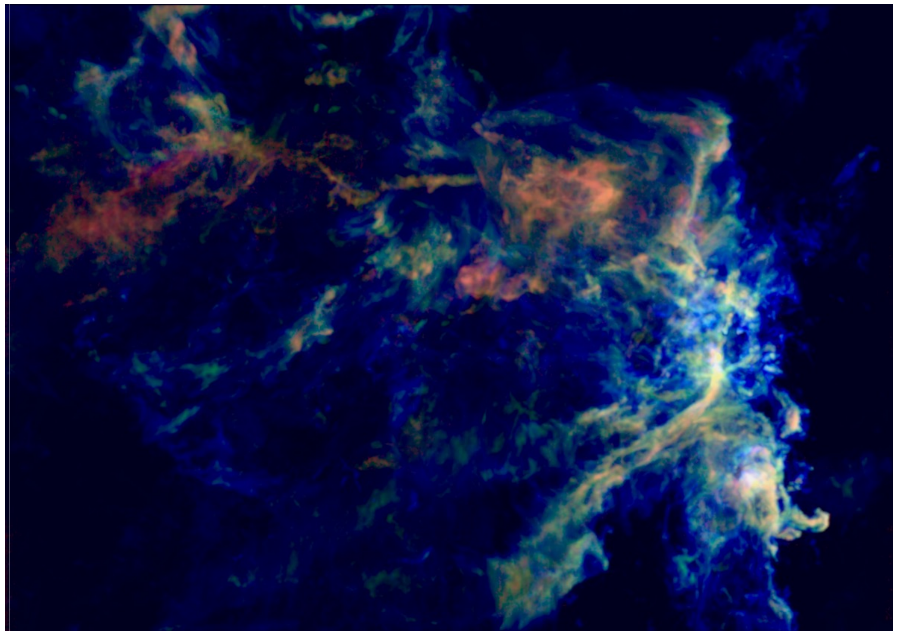
- SgrB2 : an example for molecular cloud associated to super star cluster, as in starbursts
- Combination of spectral diagnostics for the different phases

SgrB2, Santa-Maria+2021

Focusing on a nearby molecular cloud

ORION-B



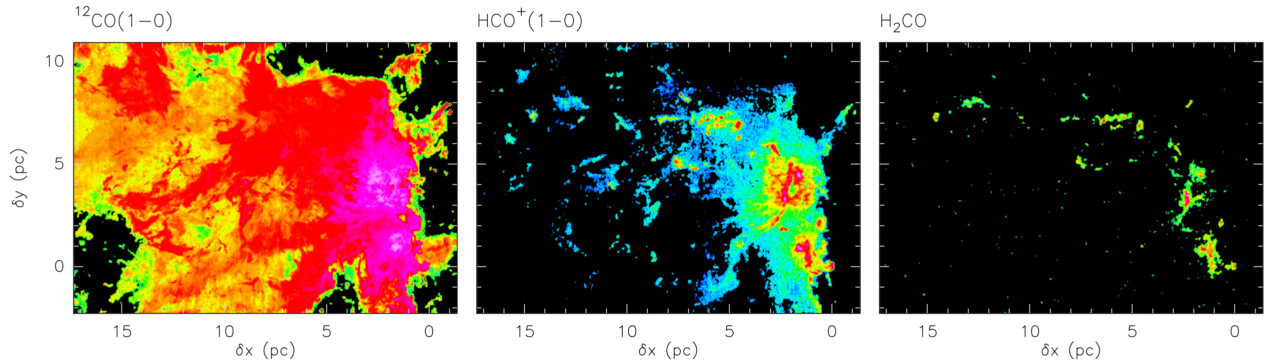


^{12}CO, ^{13}CO, $C^{18}O$ Tpeak

IRAM-30M Large program. PI : M. GERIN & J. PETY.

With I. BESLIC, L. EINIG, M. GAUDEL, H. MAZUREK, J. ORKISZ, P. PALUD, M. SANTA MARIA, L. SEGAL, V. de SOUZA MAGALHAES, M. VONO, A. ZAKARDJAN, S. BARDEAU, S. BOURGUIGNON, E. BRON, P. CHAINAIS, J. CHANUSSOT, J. GOICOECHEA, P. GRATIER, V. GUZMAN, A. HUGHES, D. LANGUIGNON, J. LE BOURLOT, F. LE PETIT, F. LEVRIER, H. LISZT, K. OBERG, N. PERETTO, A. ROUEFF, E. ROUEFF, A. SIEVERS, and P. TREMBLIN

Gas kinematics & Filaments



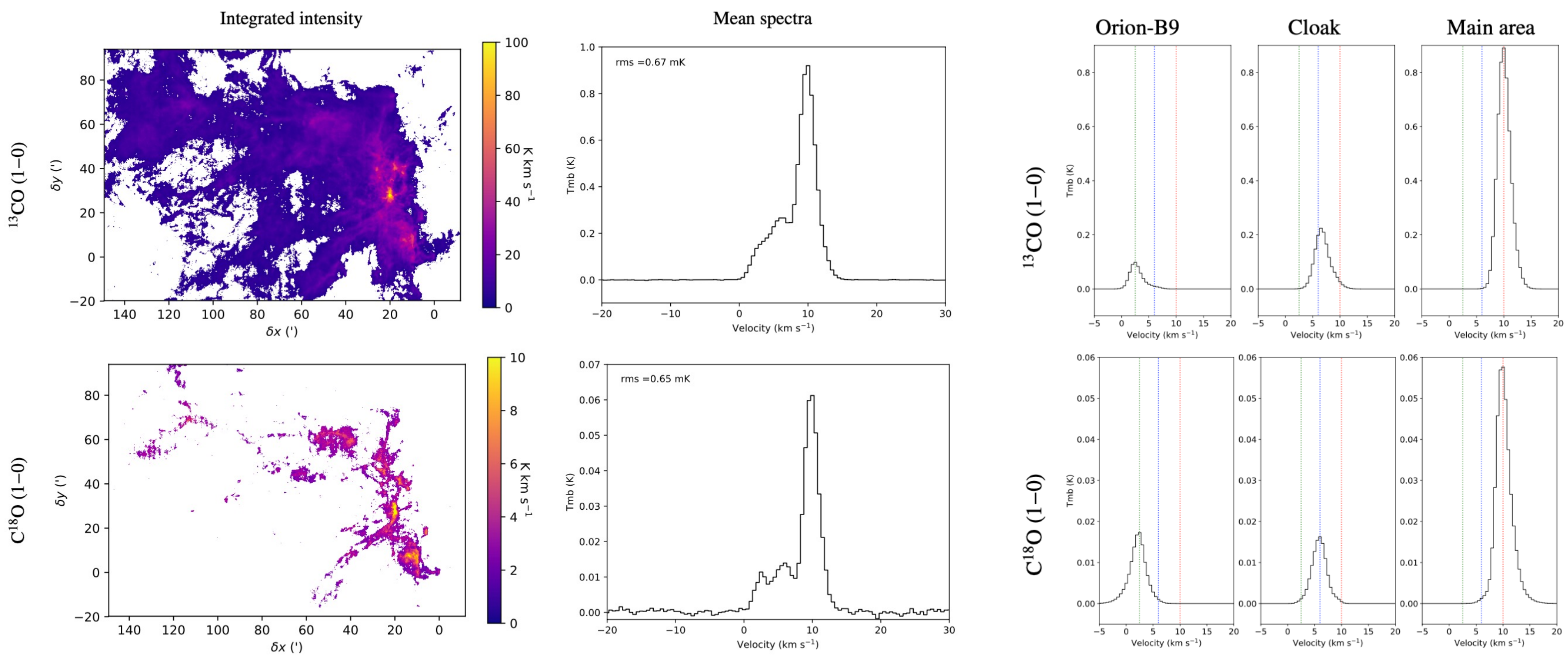
^{12}CO emission over most of the field of view

$C^{18}O$ emission spatially and spectrally concentrated

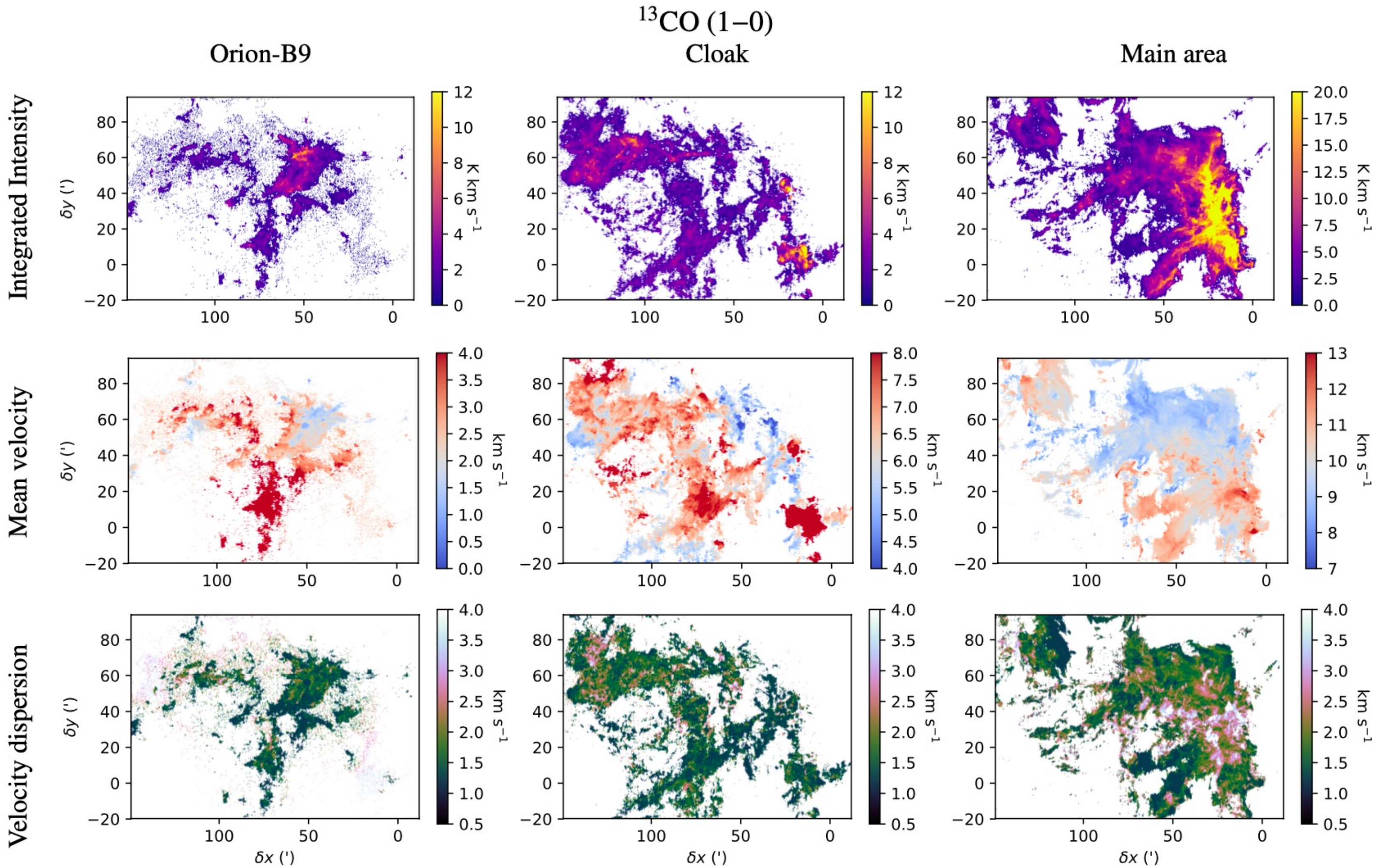
HCO^+ and HCN show extended emission from the cloud envelope

Complex spatial and velocity structure denoising and separation of velocity « layers » using ROHSA (Marshal+2020)

All velocity components associated with Orion B and at the same distance. Consistent with YSO velocities in Orion B



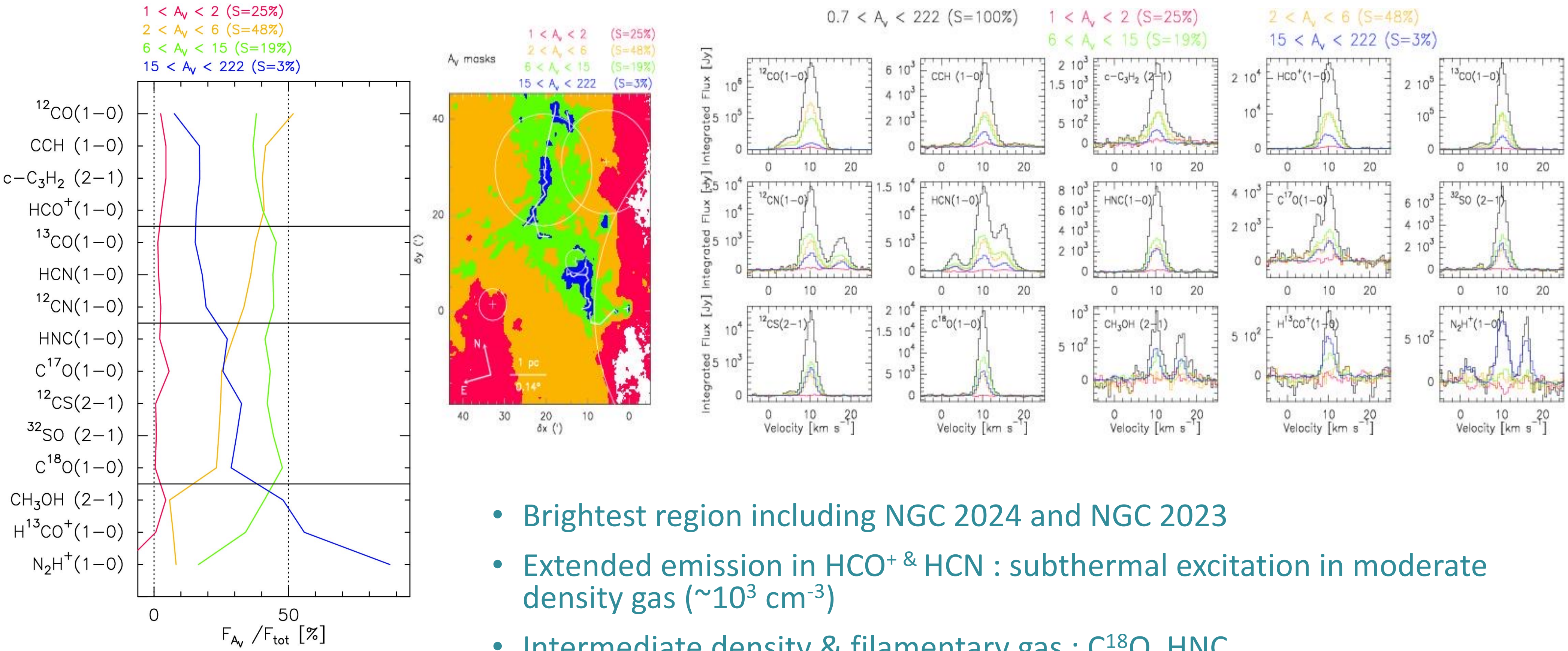
Gaudel+2023; Santa Maria 2023, Pety+2024 in prep



^{13}CO (1–0)
Orion-B9
Cloak
Main area
Integrated Intensity
Mean velocity
Velocity dispersion
δy (')
δx (')
K km s^{-1}
km s^{-1}

Gaudel+2023

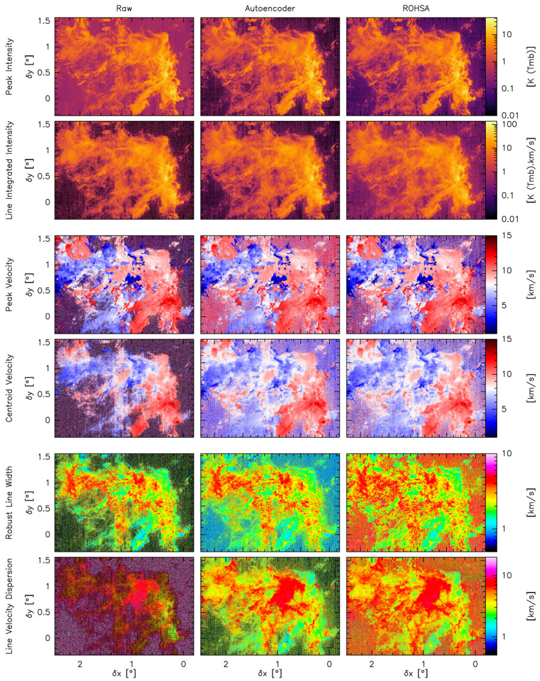
Tracing different Av / density regimes

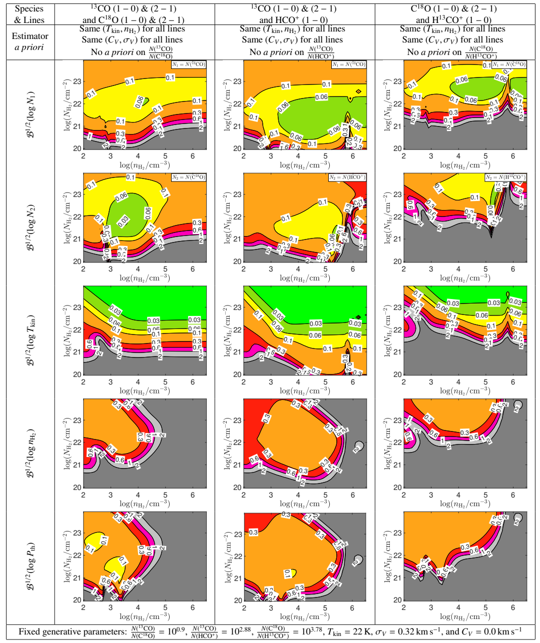


Pety+2017

- Brightest region including NGC 2024 and NGC 2023
- Extended emission in HCO^+ & HCN : subthermal excitation in moderate density gas (~10^3 cm^{-3})
- Intermediate density & filamentary gas : $C^{18}O$, HNC
- Dense and well shielded gas (n > 10^4 cm^{-3}) : N_2H^+ ; $H^{13}CO^+$, CH_3OH

Advanced data analysis & interpretation





		Method	Error factor mean	Error factor 99th per.	Error factor max	Memory (MB)	Speed (ms)
No outlier removal		near. neighbor	×13.1	×11.3	×3e5	1650	62
		linear	15.7	×2.3	×143	1650	1.5e3
	spline	linear	15.7	×2.3	×144	1650	…
		cubic	11.2	×2.2	×122	1650	…
		quintic	19.1	×2.9	×304	1650	…
	RBF	linear	10.2	96.8	×99	1650	1.1e4
		cubic	10.4	×2.1	×112	1650	1.1e4
		quintic	10.9	×2.1	×118	1650	1.1e4
	ANN	R	7.3	64.8	×**81**	**118**	**12**
		R+P	**6.2**	**49.7**	×84	**118**	13
Outlier removal on training set		near. neighbor	×13.1	×11.6	×3e5	1650	62
		linear	15.9	×2.4	×143	1650	1.5e3
	spline	linear	15.9	×2.4	×144	1650	…
		cubic	11.1	×2.2	×120	1650	…
		quintic	20.0	×2.7	×285	1650	…
	RBF	linear	10.3	97.3	×97.5	1650	1.1e4
		cubic	10.5	×2.0	×106	1650	1.1e4
		quintic	10.9	×2.0	×114	1650	1.1e4
	ANN	R	5.1	42.0	×**32.8**	118	12
		R+P	5.5	42.3	×41	118	13
		R+P+C	4.9	44.5	×44	51	14
		R+P+D	**4.5**	**33.1**	×33.8	125	**11**
		R+P+C+D	4.8	37.9	×37.6	**43**	14

- Large data volumes : automated analysis, statistical diagnostics
- Limited integraion time : denoising spectral line maps : optimum use of the data
- Precision, bias and degeneracies of the radiative transfer models : statistical tools
- Emulation of model for fast calculations and Bayesian fitting

→ Collaboration with data scientists is essential

Einig+2023, Palud+2023,Roueff+2021,2024

What’s next ?
Mapping the ISM : Galactic plane surveys

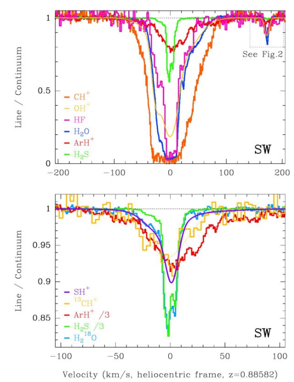
- From the ground : mapping surveys beyond CO lines for
  - Better coverage of the physical conditions
  - Kinematic information
  - Chemical information & associated physical diagnostics

→Array receivers for large single dish telescopes like IRAM-30m

- From space : mapping surveys of FIR fine structure lines ([CII], [NII], [OI], ..) with high spectral resolution
  - From the very low density phases to diffuse molecular gas
  - Feedback phenomena including large scale winds and outflows
  - Tomography of the MW together with extinction data
  - Energy flows from cooling power (need some FIR CO & H_2O lines)
- From space : dust emission polarimetry

→ Context for extragalactic data up to high redshift

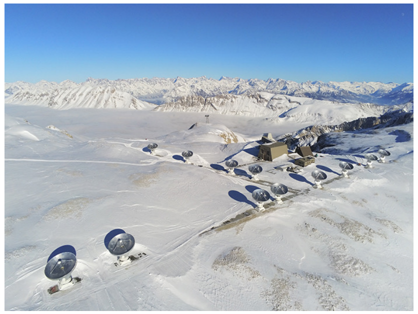
Müller+2021



Müller+2017

What's next ? Star and planet forming material

- Far infrared spectroscopy of planet forming disks : HD, H_2O, OI, as in the FIR probe projects
  - Total gas content, depletions, position of the snow line, tomography from the line profiles, evolutionary effects
  - High spectral resolution is key for line profile and line/continuum separation
- IR imaging spectroscopy with JWST
- Ground based interferometers NOEMA, ALMA Wide Sensitivity Upgrade (2030+) with 2x (8 – 16 GHz) at high spectral resolution, ngVLA, MeerKat




SOFIA
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY
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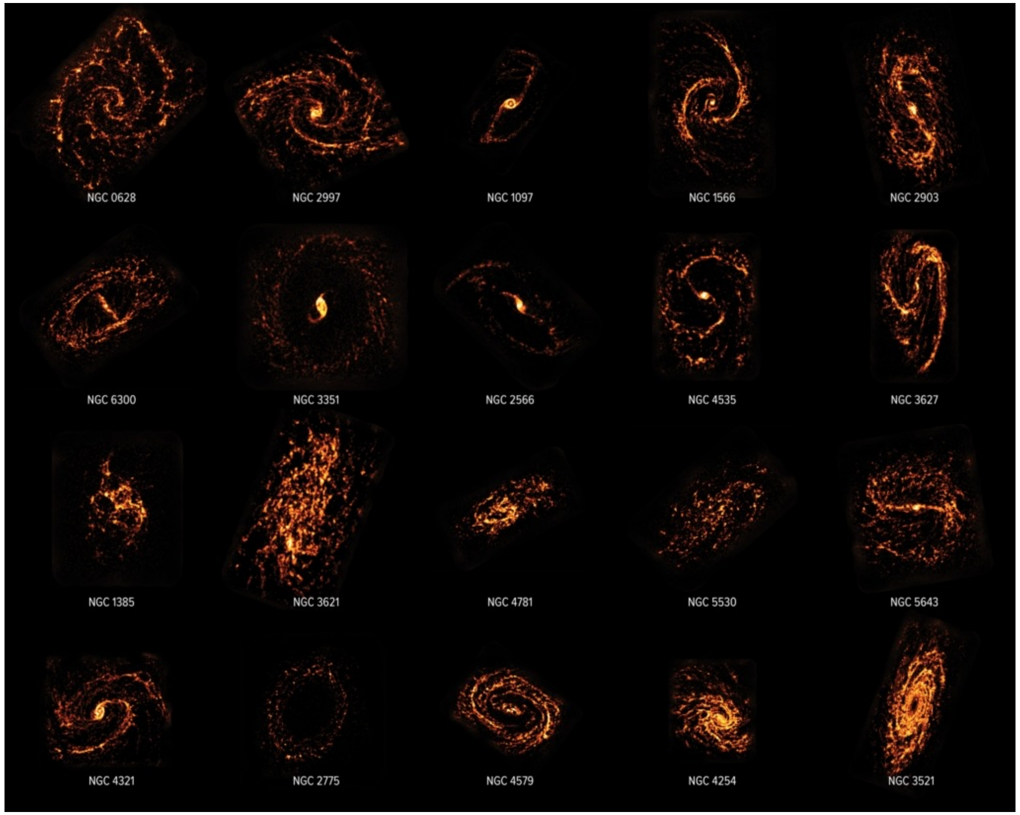
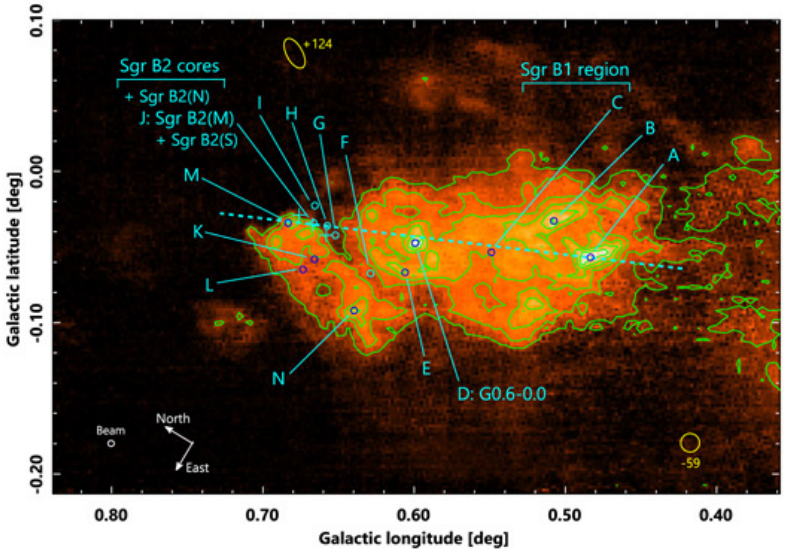
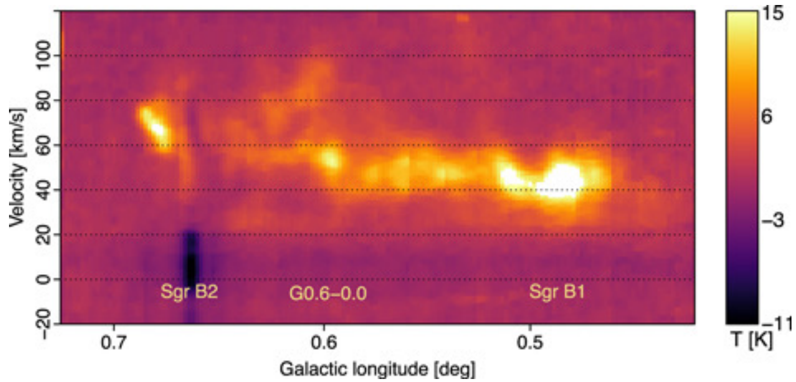
In nearby galaxies

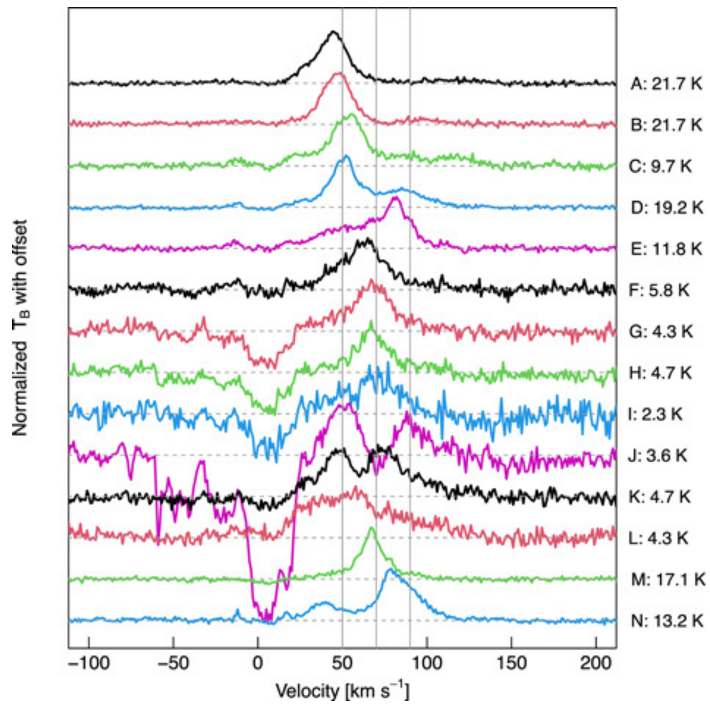
PHANGS : ALMA+VLT

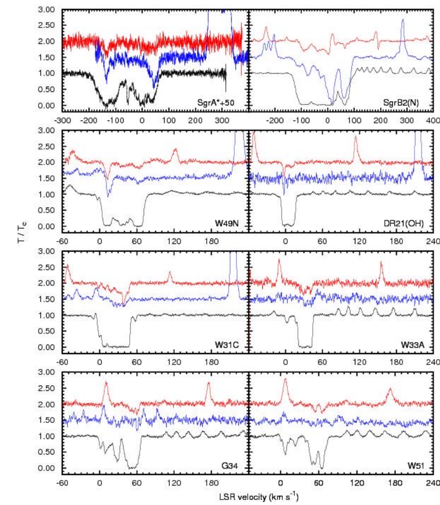


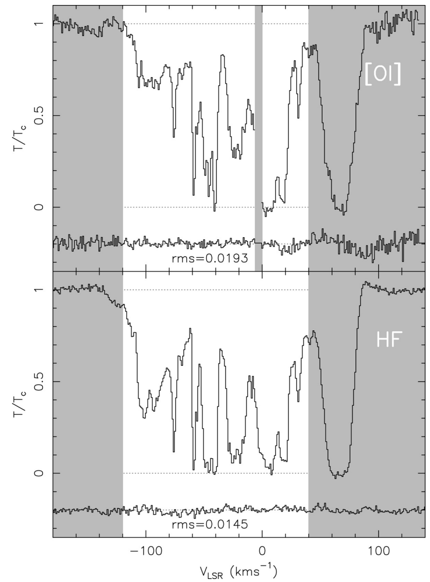
Complexity of line profiles











[CII] with SOFIA

Herschel

SgrB2, Harris+2021, Godard+2012, Lis+2014, Lis+2023