Non-equilibrium chemistry in the cold diffuse interstellar medium

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with the collaboration of
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- A longstanding problem: how to incorporate C and O in the chemistry of diffuse clouds?
- Where complex physics meets stiff chemistry: outlines of a model
- The guidance of observations:
  - towards high spectral resolution observations of $^{13}CH^+$(1-0)
  - the location of large HCO^+ abundances in diffuse molecular gas

Warm glitters in the cold diffuse ISM

• Large abundances of molecules which cannot form in cold gas are observed in the CNM:

CH^+: $C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k = 4640$K)

e.g. Crane et al. 1995; Gredel 1997

HCO^+: a daughter molecule of CH^+ via $CH_3^+ + O \rightarrow HCO^+ + H_2$

Liszt & Lucas 2000; Falgarone et al. 2005 submitted

H_2O and OH: $O + H_2 \rightarrow OH + H$ ($\Delta E/k = 2980$K)

Neufeld et al. 2002, Plume et al. 2004

• large rotational excitation of H_2 in the diffuse medium,
not ascribed to UV photons
FUSE and ISO-SWS data

e.g. Gry et al. 2002, Lacour et al. 2005, Falgarone et al. 2005

Formation energy required $>>$ available thermal energy

Reservoirs:

• non-thermal turbulent and magnetic energy, $\sim 30\times$ thermal on average

• H_2 formation energy, a fraction of 4.7 eV

First detection of $^{13}CH^+$(1-0)

CSO 10.4m telescope,

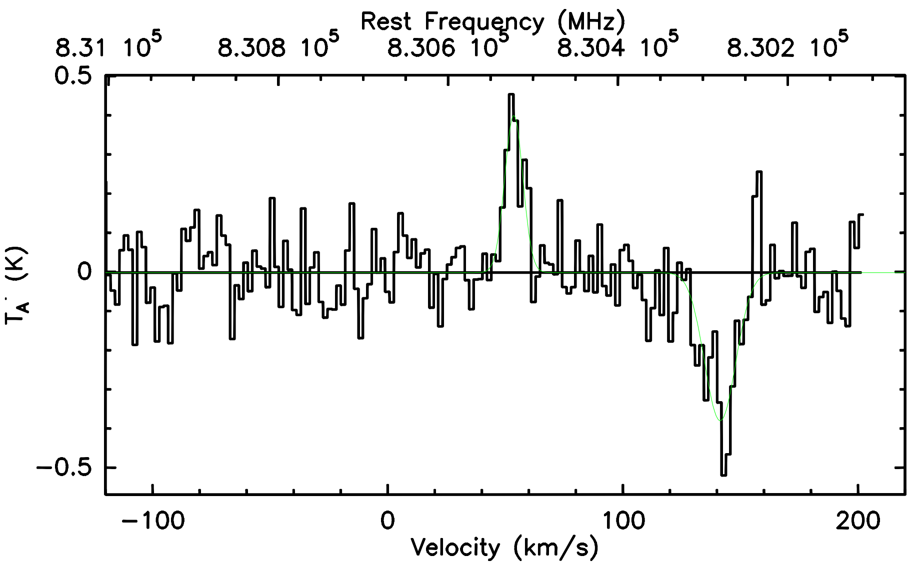
dust thermal continuum removed

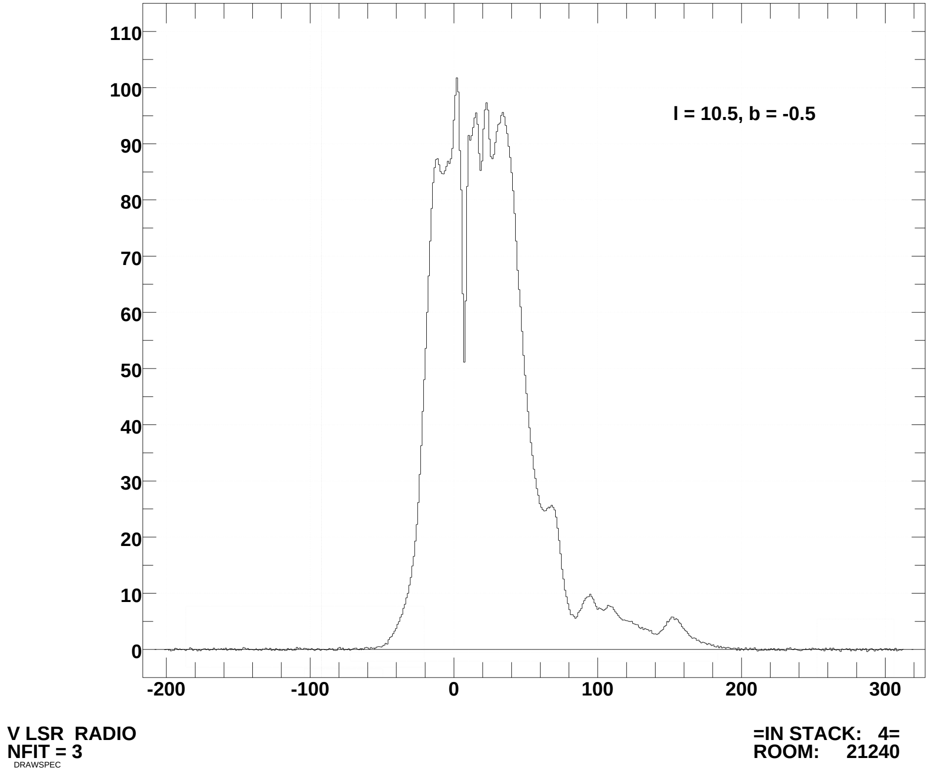
strong background source G10.6-0.4:

10^3 Jy at 350 μm Mueller et al. 2002

HI survey Leiden Dwingeloo

Hartmann & Burton 1997

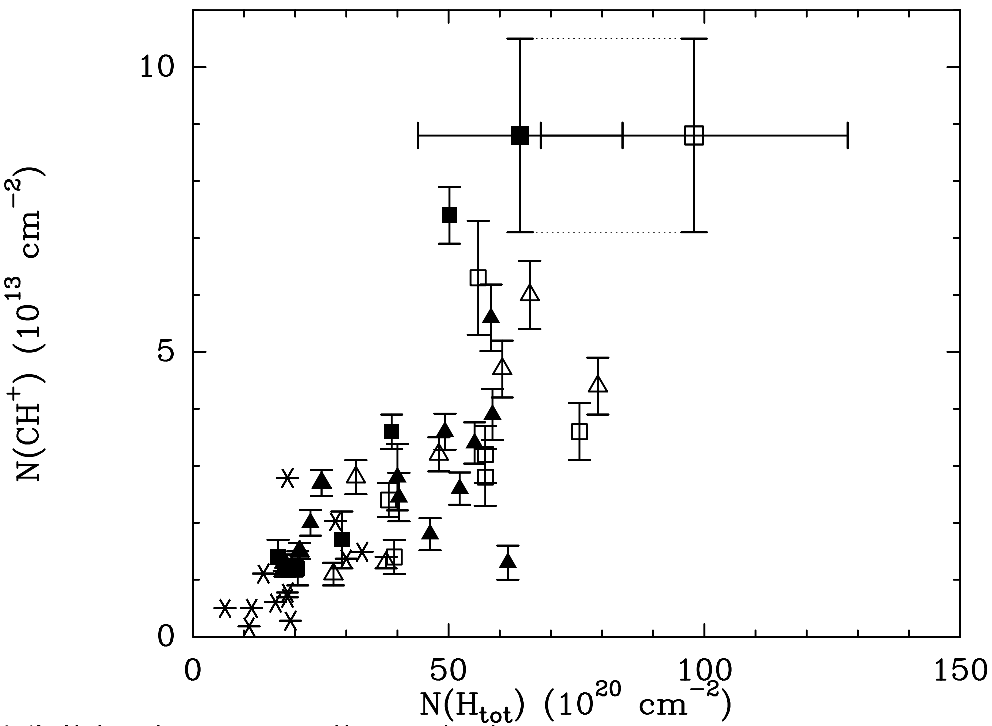




Laboratory measurement of $^{12}CH^+$(1-0) ν=835.079(1) GHz Pearson 2005
Predicted $^{13}CH^+$(1-0) ν =830.131 GHz, mass scaling
If absorption line originates in the cold HI (self-absorption dip) $\nu = 830.132(3)$ GHz

Falgarone, Phillips & Pearson 2005 submitted

Comparison with results from absorption lines in the visible



Assumed [$^{12}CH^+/^{13}CH^+$]=40

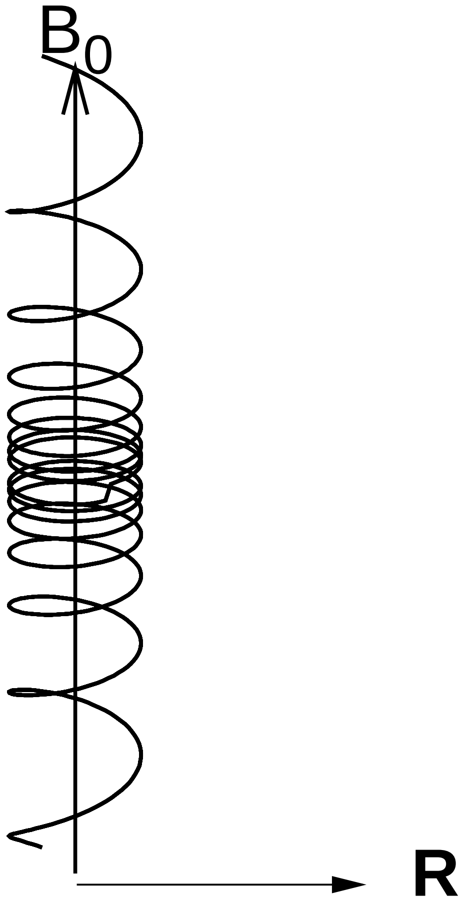
Visible and submm: similar sensitivities,

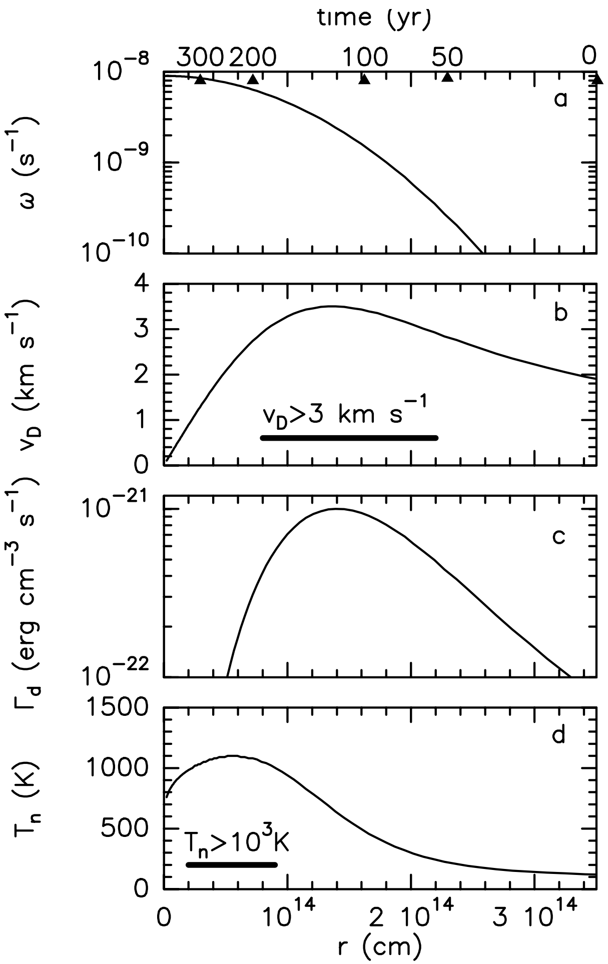
Submm line detections: high spectral resolution and possible detections in emission (dust FIR excitation in diffuse gas)

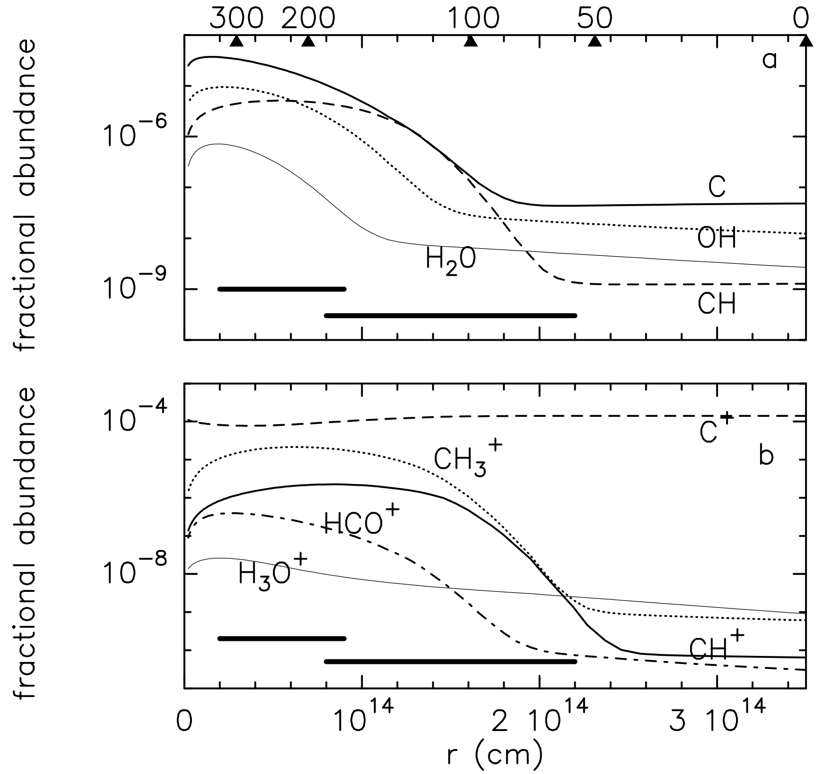
Visible data: small symbols

Crane et al. 1995, Gredel 1997

A framework for non-equilibrium chemistry



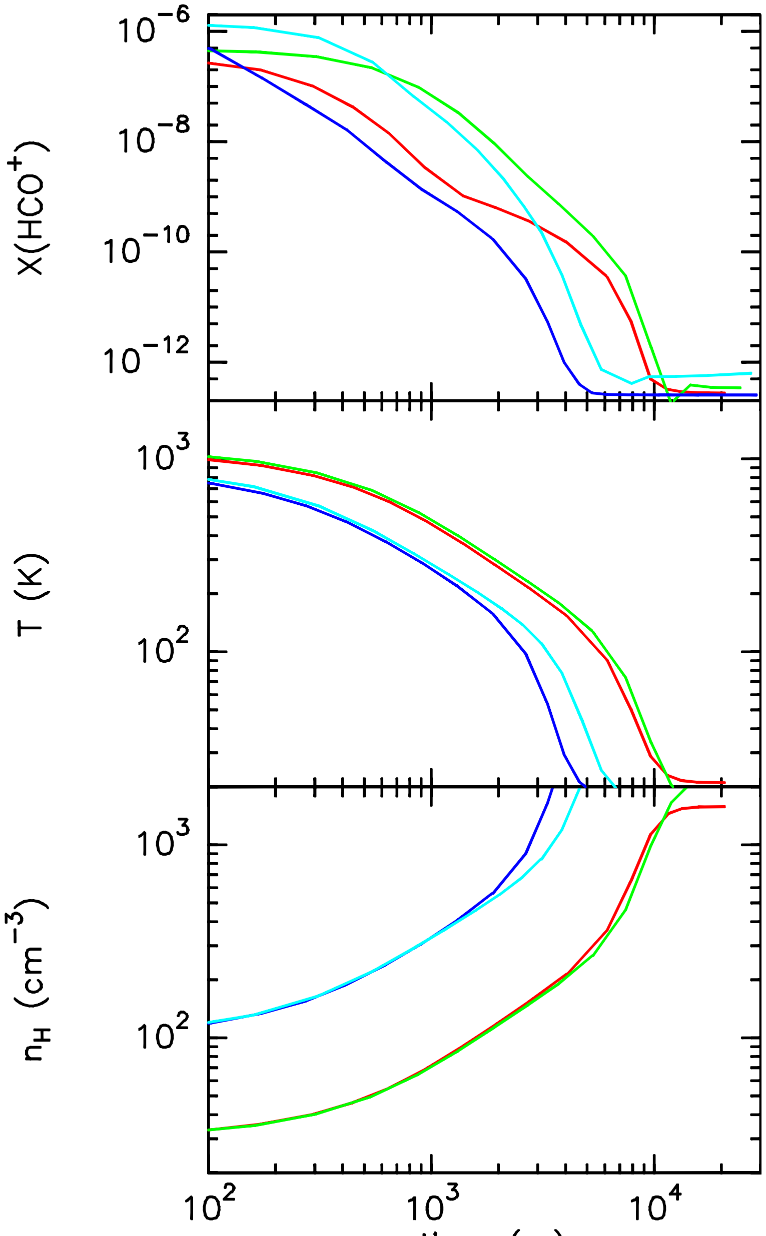


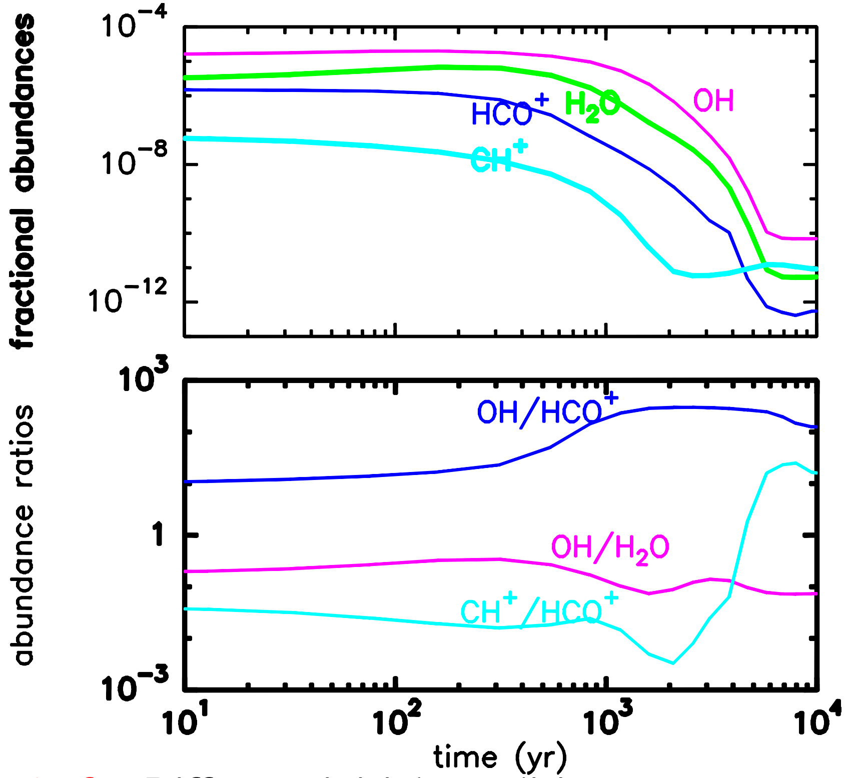


Heating and triggering of warm chemistry within **only a few 100 yr**

Joulain et al. 1998

After vortex blow-up, isobaric thermal and chemical relaxation





Left: Different initial conditions,

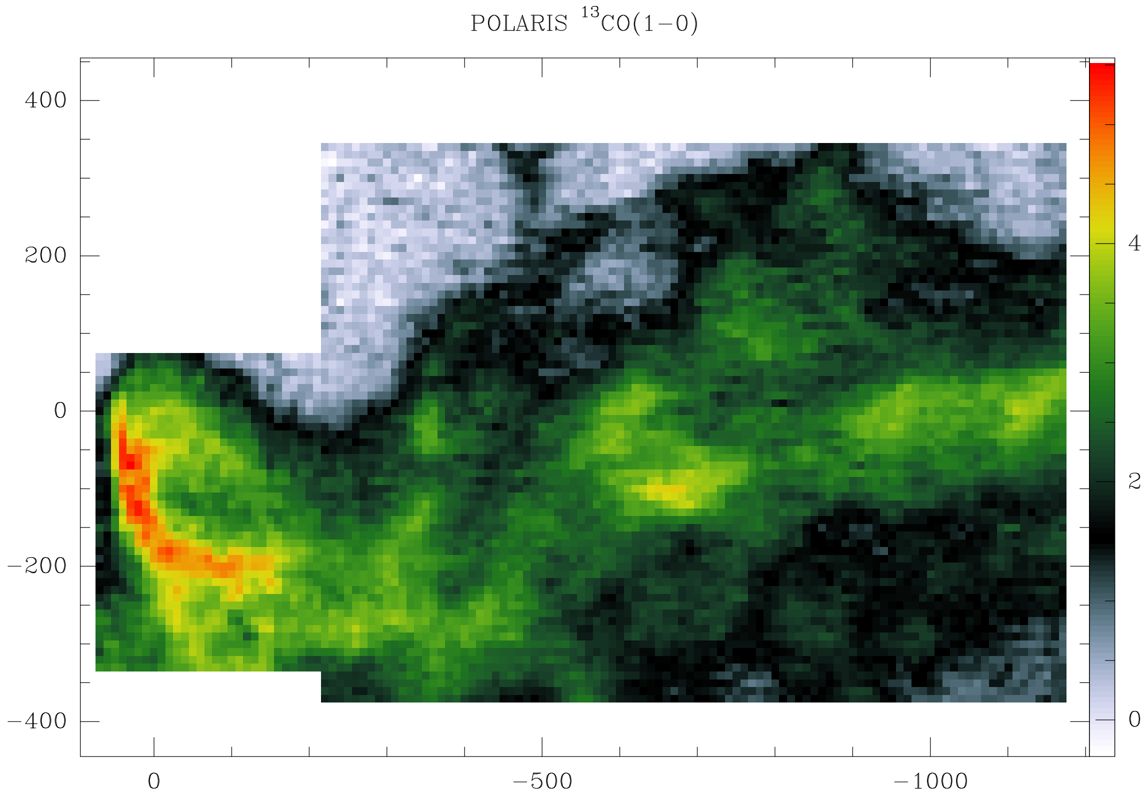
UV shielding: $A_v = 0.2$ and 1 mag

Steady-state HCO$^+$ abundances 10^{-10} to 10^{-12}

Warm chemistry signatures persist over several 10^3 yr.

Falgarone, Pineau des Forêts, Hily-Blant & Schilke, submitted

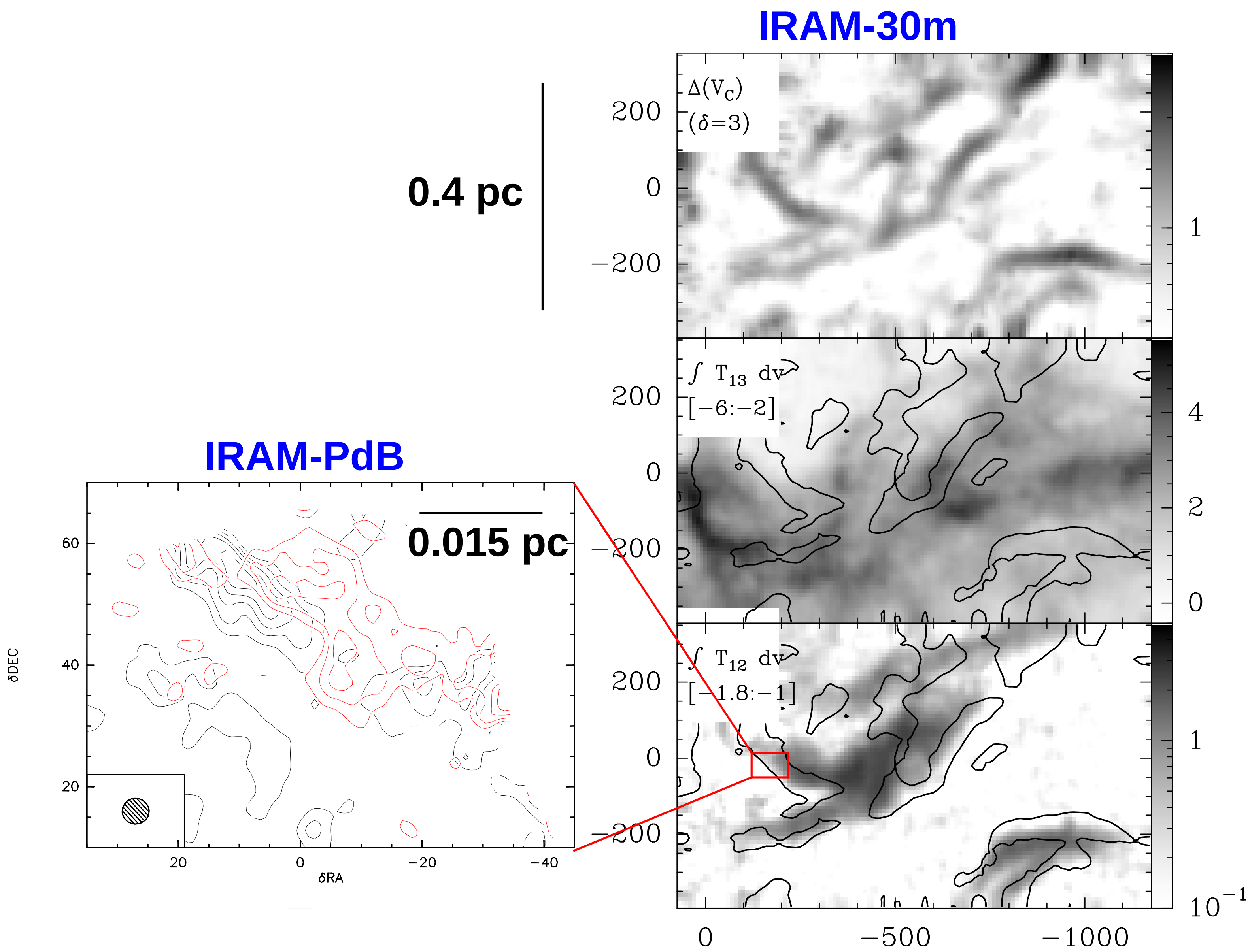
Turbulent environment of a low mass dense core



^{13}CO(1-0) IRAM-30m map of a dense core in a high latitude cloud (Polaris flare), size 1.5 $\times$ 1.2 pc

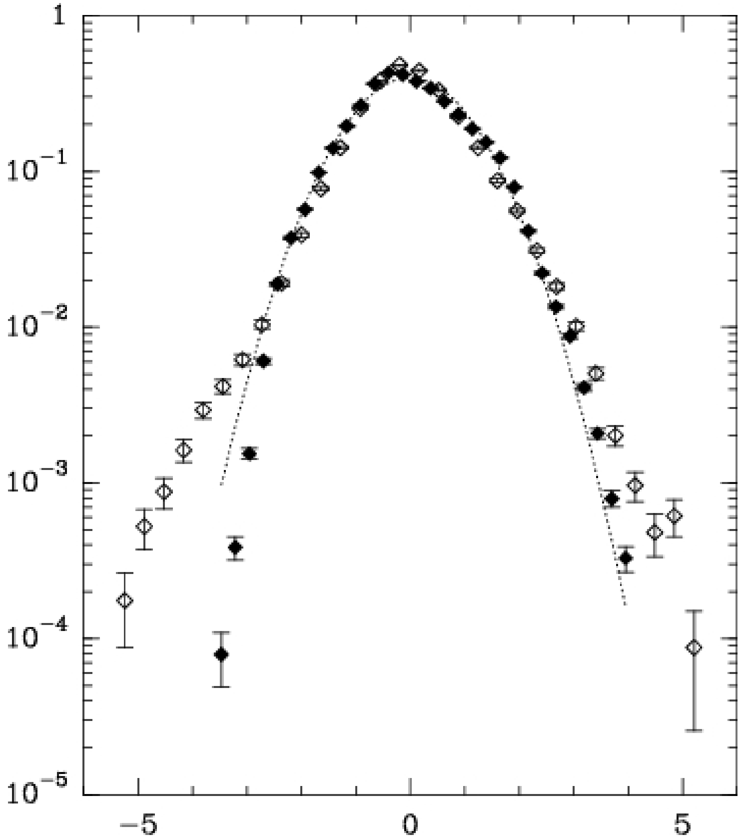
8000 spectra, resolution 22 arcsec, 0.015 pc, spectral resolution $<$ 0.1 km/s

The regions of largest velocity shear (CVIs)



Hily-Blant, Falgarone, Pety 2005

Characteristics of the regions of largest CVIs

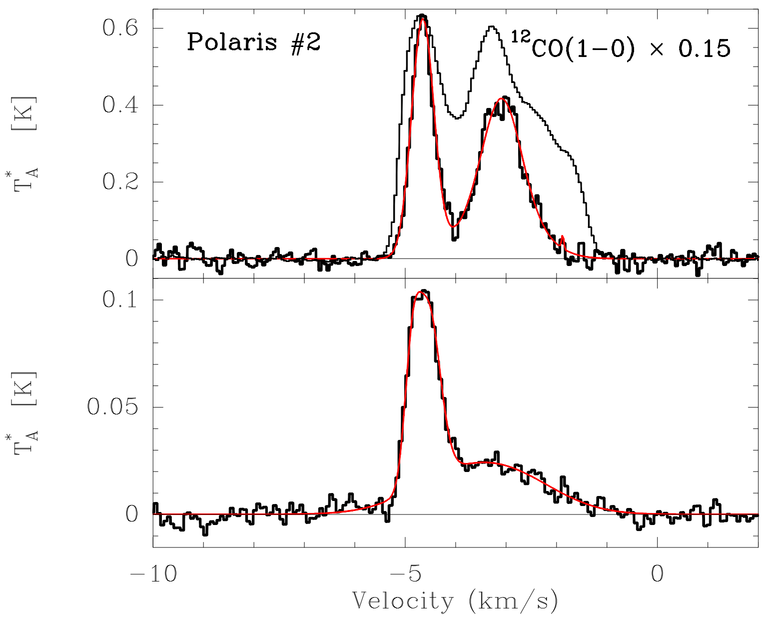


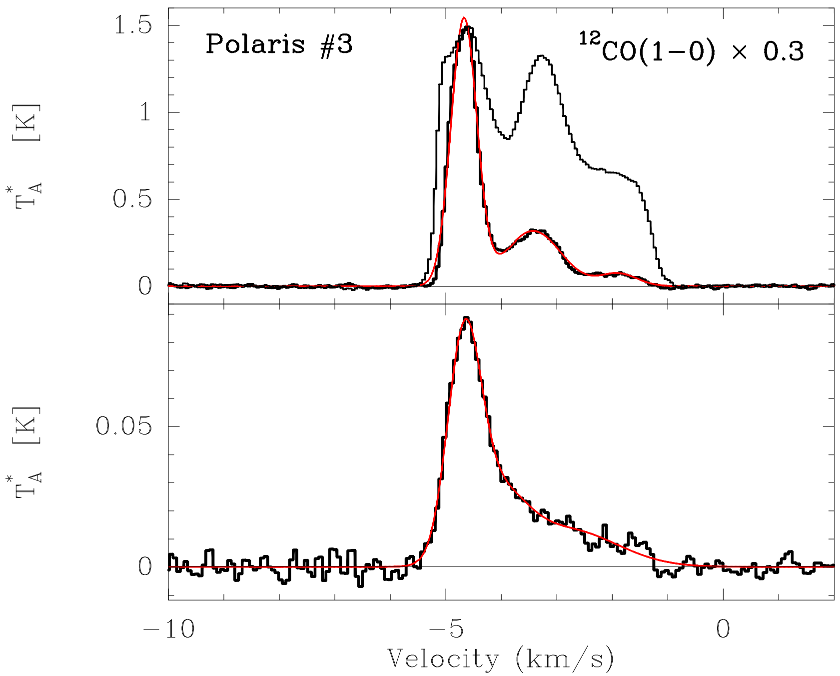
PDFs of CVI,
lag = 18 (solid), 3 (open) pixels

(Hily-Blant et al. 2005)

- **network of filaments,** thickness ~ 0.05 pc
- not density maxima but associated with lower density, warmer gas
- **substructure** down to 700 AU
- largest shear ~ 200 km s^{-1} pc^{-1}, or timescale ~ 10^3 yr
- HCO^+ orders of magnitude above steady-state values

IRAM-30m weak HCO^+(1-0) emission lines

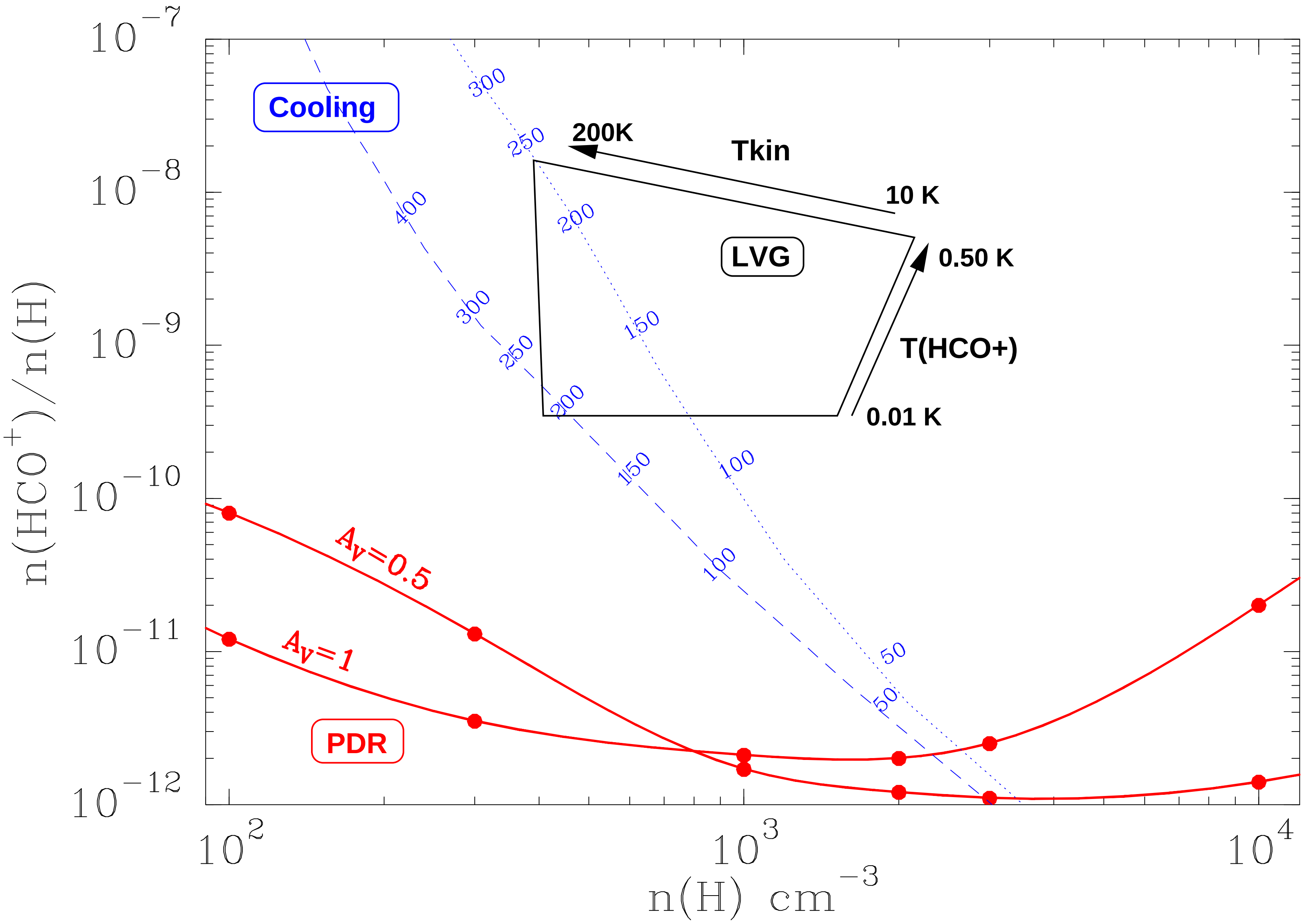




Top: ^{12}CO(1-0) (black) and ^{13}CO(1-0) (red), bottom HCO^+(1-0)

Falgarone, Pineau des Forêts, Hily-Blant & Schilke, submitted

HCO^+(J=1-0) observations confronted to models



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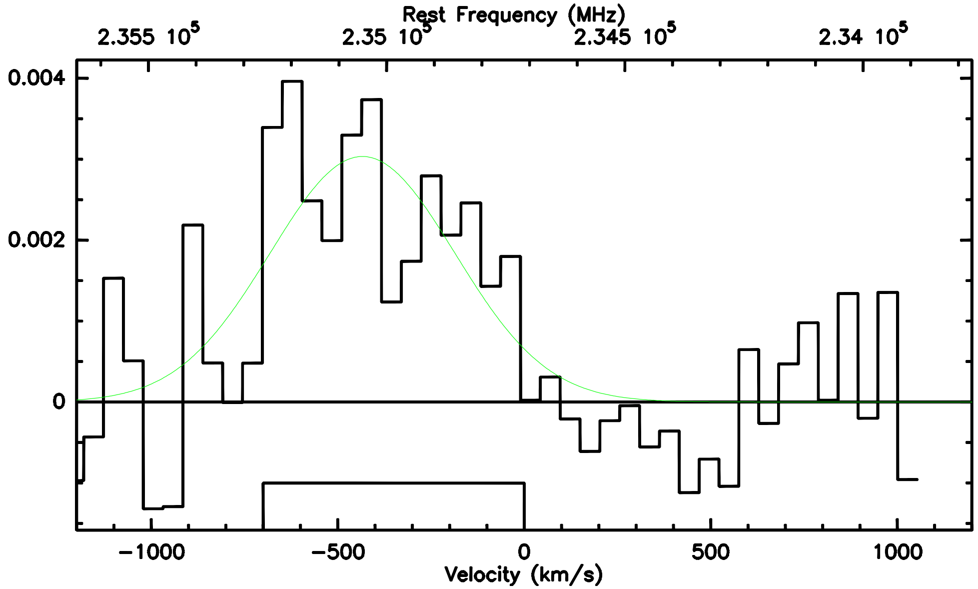
Summary

- Source of non-thermal trigger of the warm chemistry in the CNM still elusive: opening of possible ground based $^{13}CH^+$(1-0) observations
- If driven by intermittent dissipation of its turbulence:
• a few 10^{-2} of warm gas are sufficient to reproduce the observables
• possible sites of the warm chemistry: the locus of largest velocity shears = network of narrow filaments of thickness ~ 0.05 pc
• large velocity shear observed at 700 AU scale (3 mpc)
• warm chemistry signatures survive a few 10^3 yr after the end of the dissipation burst
• powerful tracers of hidden masses of cold gas (H2EX project)

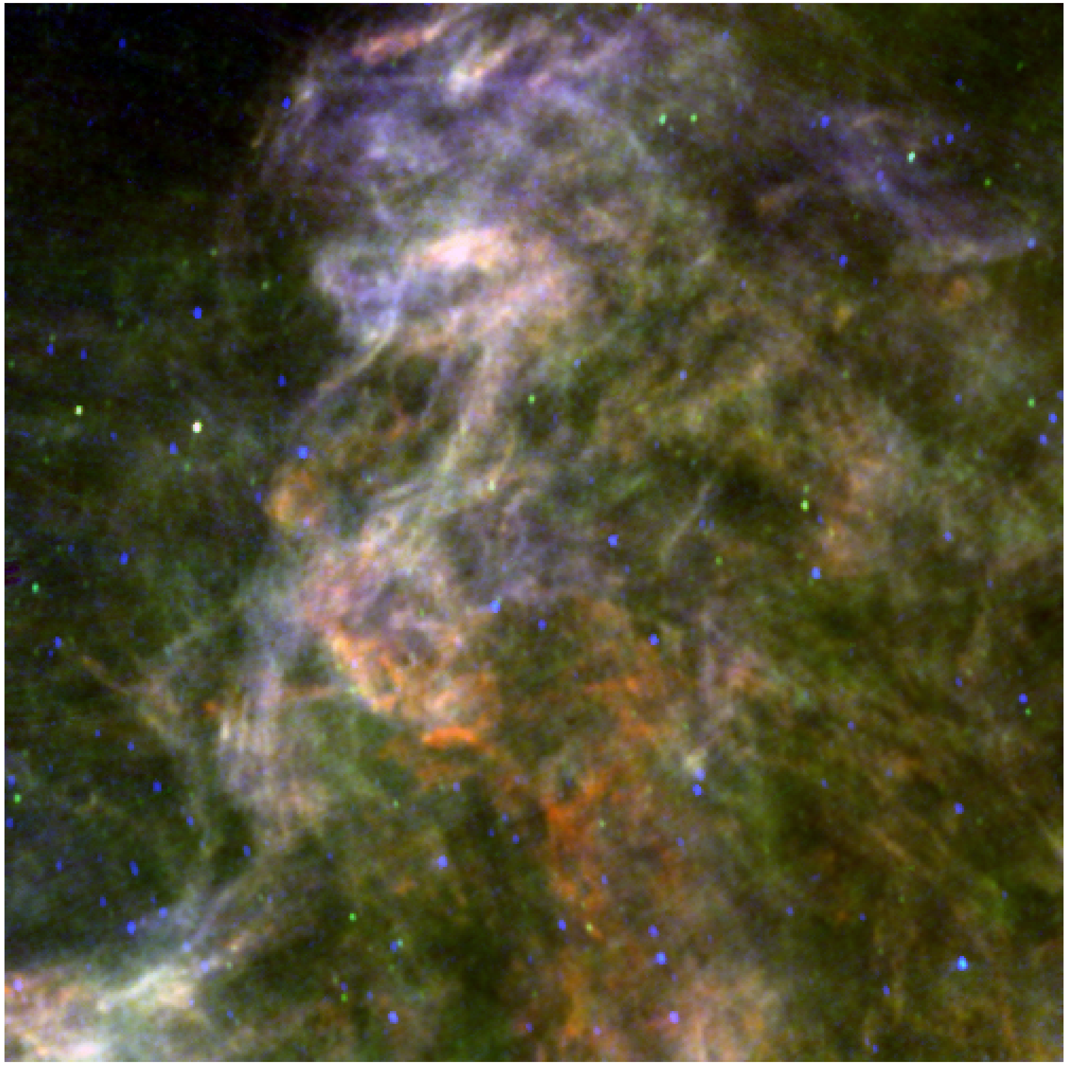
Tentative detection of CH^+(1-0) in the Cloverleaf quasar



Average column density in the CSO beam:
$\overline{N}(\mathrm{CH}^+) = 4 \times 10^{12}$ cm^{-2} for FIR $u_\nu = 10^3 \times u_\nu(MR)$
Estimated gas mass traced: $\sim 10^{11}$ $M_\odot$ for $X(\mathrm{CH}^+) = 4 \times 10^{-9}$
Line shifted by 400 km s^{-1} from the CO lines

Falgarone, Phillips, Yoshida, Cernicharo, Black, Pearson in prep.

FIR image of the Polaris Flare



Reprocessed IRAS maps: Miville-Deschênes & Lagache (2005)

$\sim 10^\circ \times 10^\circ$ or 20 pc, 100μm red, 60μm green 12-25μm blue