Ionized components in star forming regions by spectroscopic observations

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Introduction:
Star-formation & magnetic fields

Scientific Background

- Star Formation
  - Wide coverage of density and temperature (too general comments)
  - Magnetic field – important role – how at earliest stage?
  - Jet/outflow – magnetic field involved – launching mechanism?
  - Atomic/ionized component. – less dense ionized regions
- Planet Formation (ALMA)
  - High resolution is a key.
  - New radical ideas may be needed ([N II])

Formation of Stars and Planets

Magnetic field
Angular momentum
in a core scale
$B_{core}R_{core}^2$

Magnetic field and removal
angular momentum in a
jet/outflow
$B_{core}R_{core}^2 - B_{disk}R_{disk}^2 - B_{*}R_{*}^2$

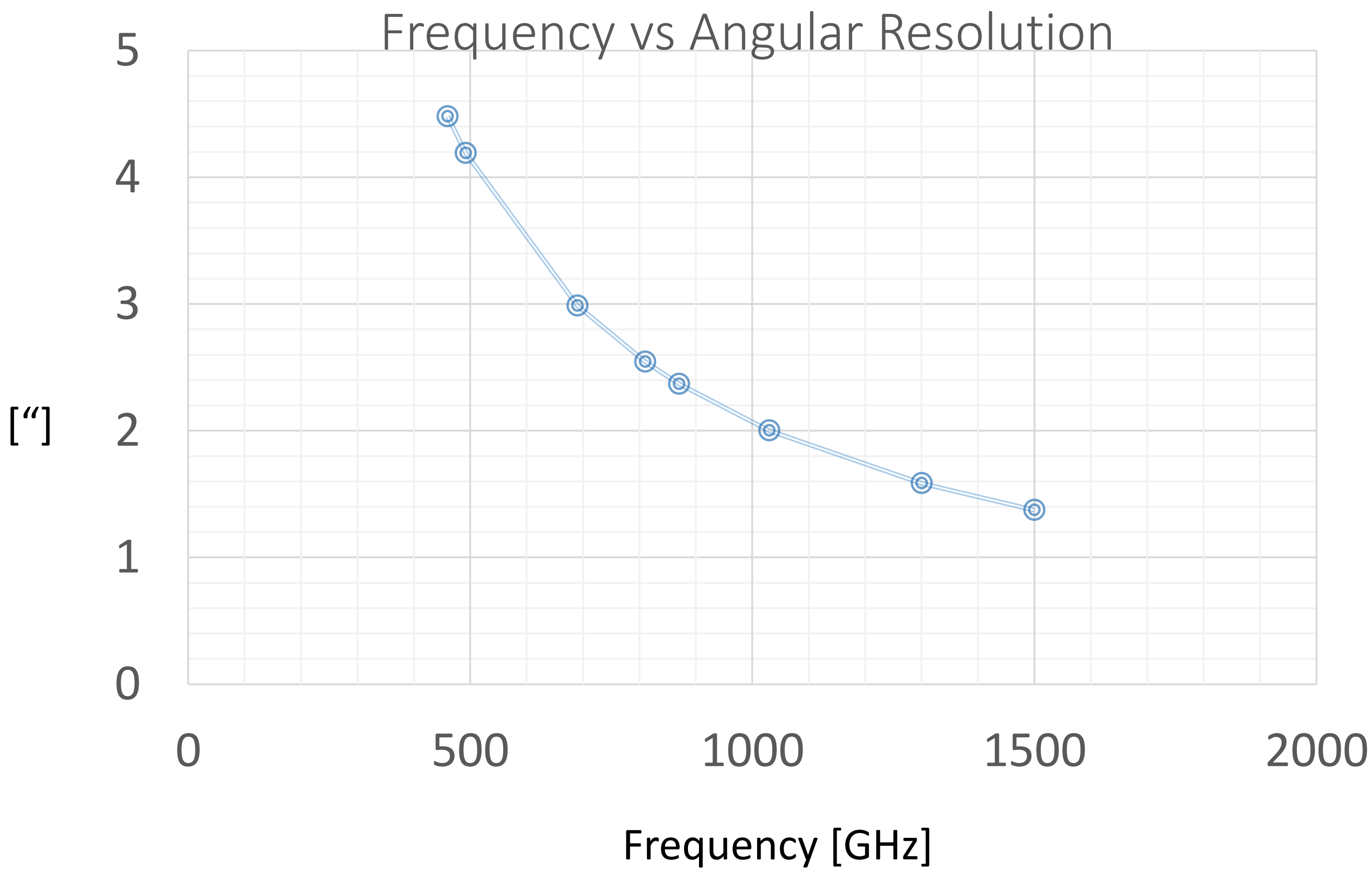
Core scale
10^{3-4} au

Jet/Disk scale
10^{0-3} au

Stellar scale

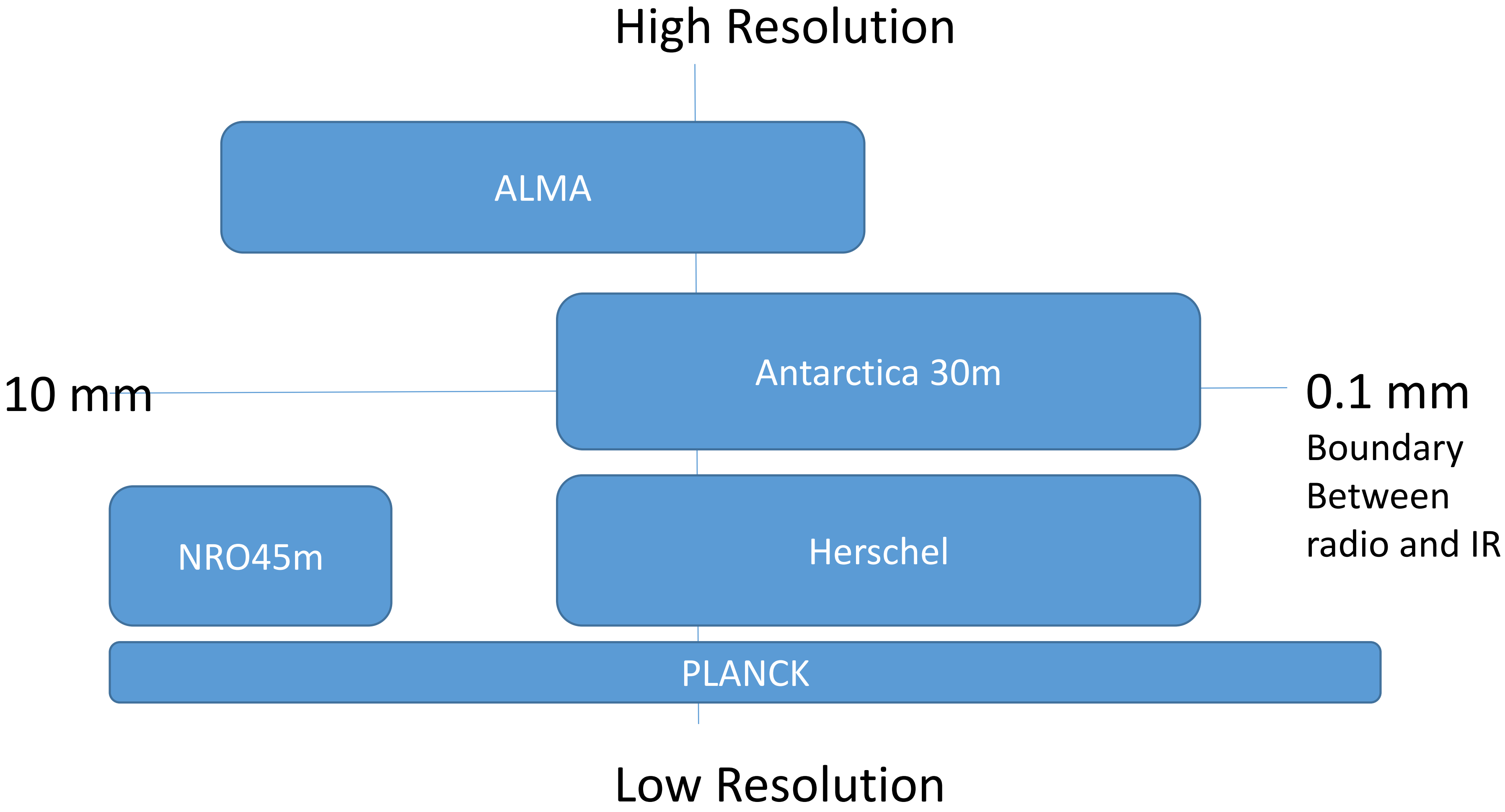
Antarctica 30 m telescope

- Ground Based Telescope
  - Large Collecting Area
  - Good Angular Resolution (a few arcsecs)
  - Potentially wide frequency coverage
- Antarctica Site
  - New atmospheric window
  - Advantage : inaccessible windows from MK or Atacama
  - Disadvantage: Single dish
- Targets:
  - size >> angular resolution



Complemental Instrument

- Herschel
- ALMA
- NRO45m



High Resolution

ALMA

10 mm

Antarctica 30m

0.1 mm

Boundary
Between
radio and IR

NRO45m

Herschel

PLANCK

Low Resolution

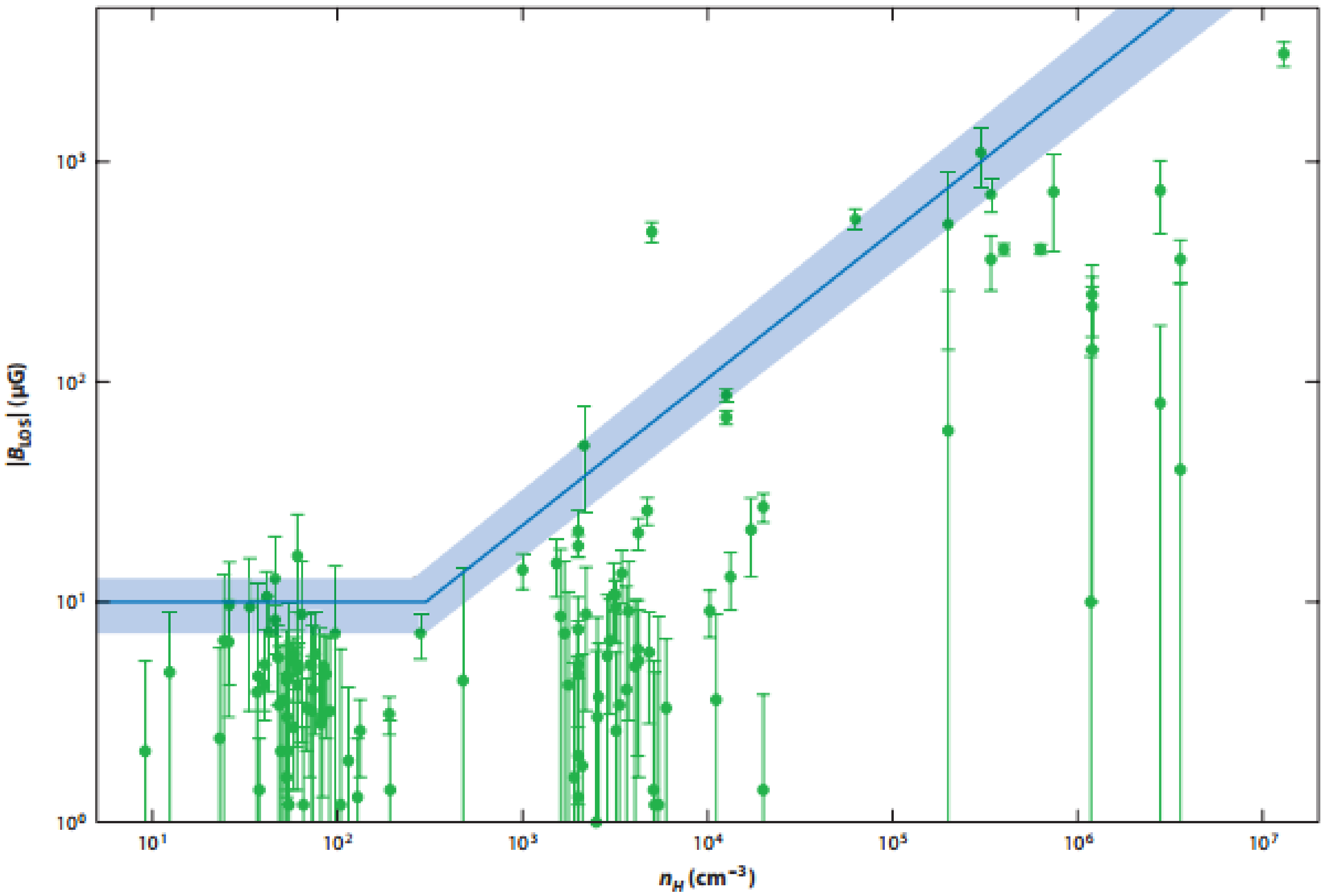
Target (2” resolution)

	size	D=10 pc	D=150 pc	D=1kpc	D=10 kpc
Debris Disk	100 au	20 au	300 au		
Protoplanetary disk	100 au		300 au		
Low-mass star	100-10000 au		300 au	2000 au	
Low-mass jet/outflow	1-10000 au			2000 au	
Hot core (IRDC)	100-10000 au			2000 au	0.1 pc
high-mass outflow	100-10000 au			2000 au	0.1 pc
Cloud (CCC)	1-5 pc				0.1 pc
GMC (SNR)	10-100 pc			2000 au	0.1 pc

Measurement of Magnetic Field

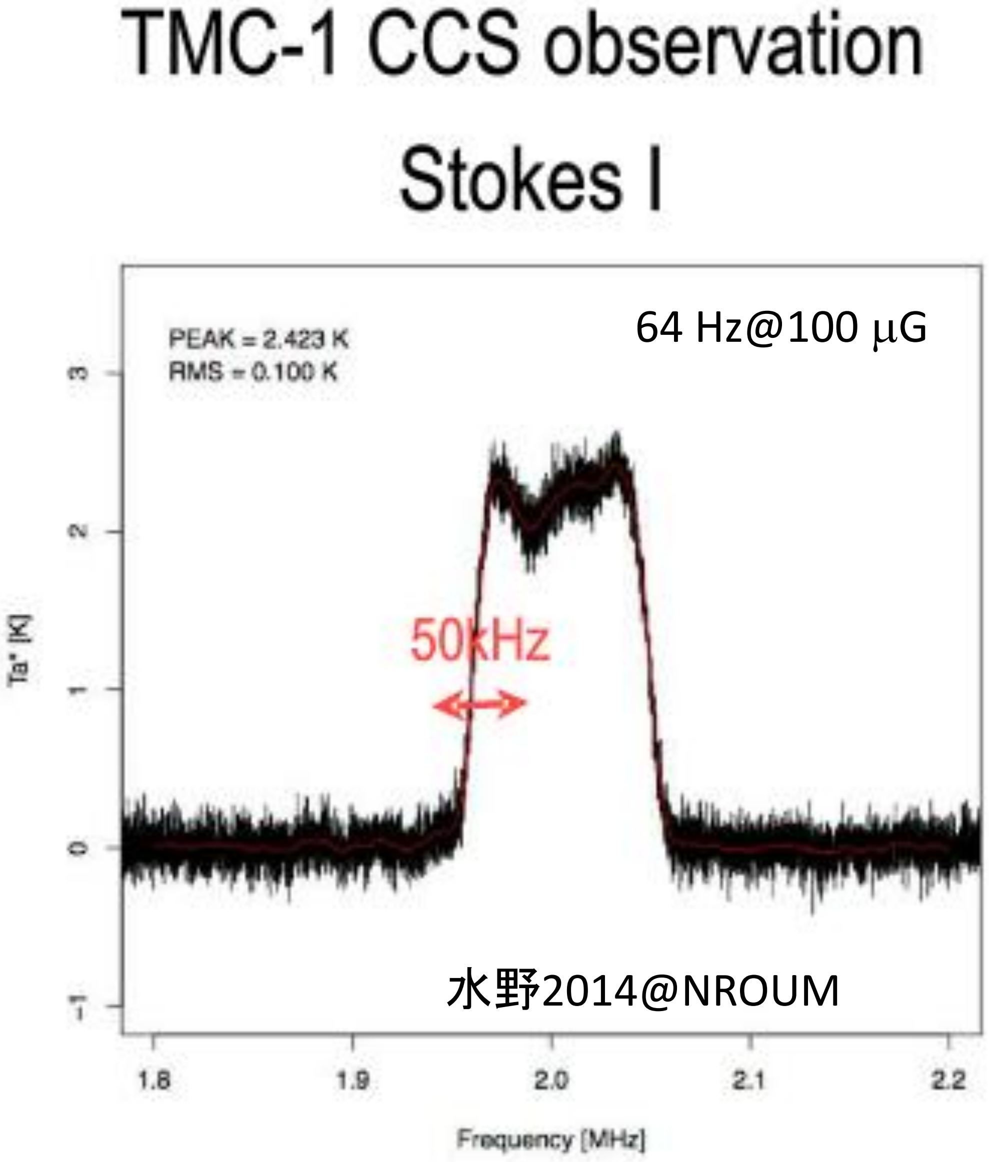
- See Momose-san’s Presentation in continuum

- Zeeman (HI, OH, CN)
  - Circular polarization - measurement |B| along the line of sight.



Measurement of Magnetic Field

- Zeeman in reality
  - Extremely difficult (e.g. instrumental calibration)
  - E.g. Δf ~ 64 Hz @100μG in CCS at 45 GHz << thermal broadening



64 Hz@100 μG

水野2014@NROUM

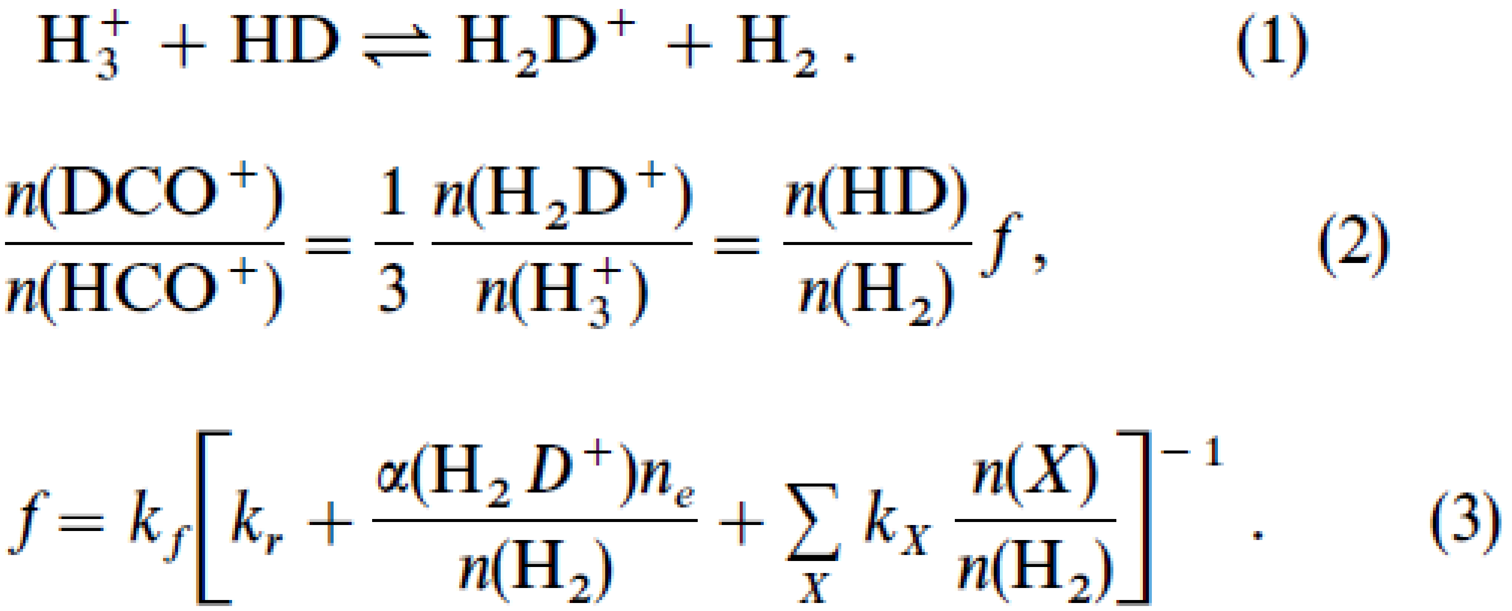
Ionization Fraction

Measurement of Ionization Fraction

- If zero, no magnetic force is exerted.
- Ambipolar diffusion
  - Dense cores slippage of gas through the ambient magnetic field.
  - Time scale critically depends on the ionization fraction.

- Ionization fraction $x(e)=n_{e-}/n_H$
  - ~ 10^{-7} from previous studies

Measurement of Ionization Fraction: DCO^+/HCO^+



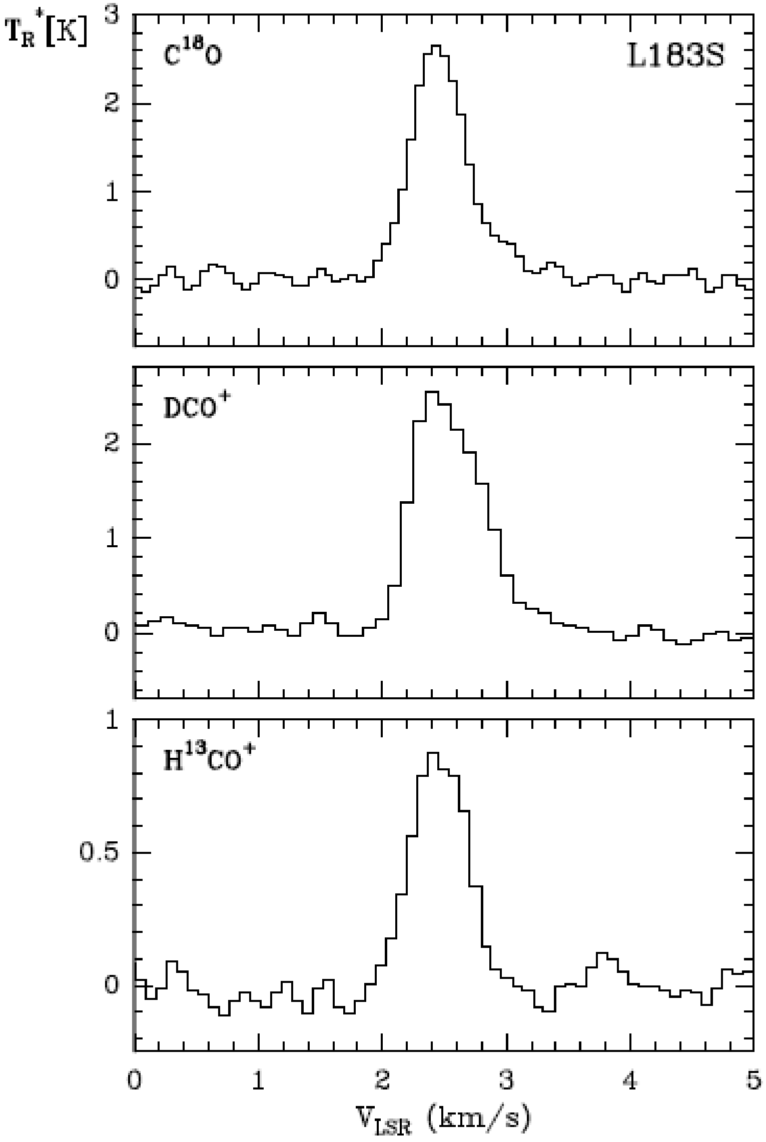
$$H_3^+ + HD \rightleftharpoons H_2D^+ + H_2\ . \qquad (1)$$

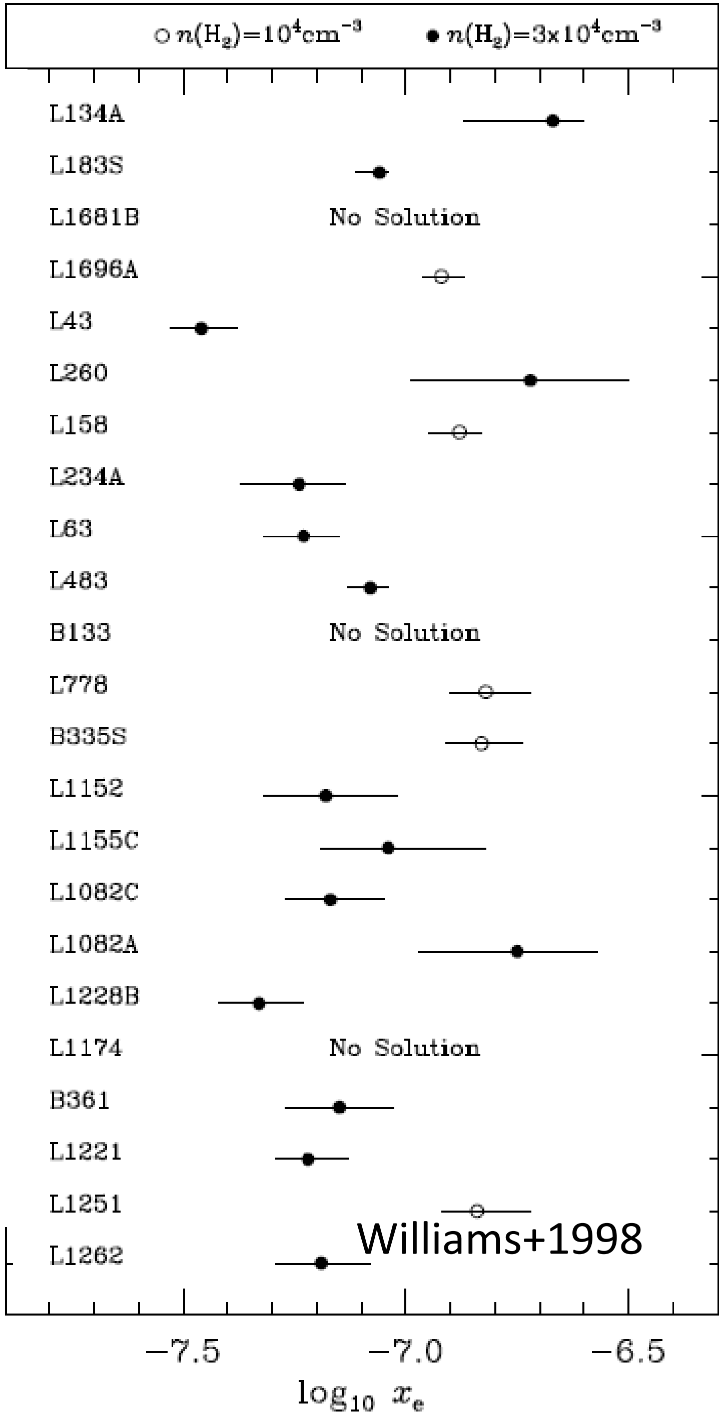
$$\frac{n(DCO^+)}{n(HCO^+)} = \frac{1}{3}\frac{n(H_2D^+)}{n(H_3^+)} = \frac{n(HD)}{n(H_2)} f\,, \qquad (2)$$

$$f = k_f \left[k_r + \frac{\alpha(H_2D^+) n_e}{n(H_2)} + \sum_X k_X \frac{n(X)}{n(H_2)} \right]^{-1} . \qquad (3)$$

- [e$^-$] ~ $10^{-7+-0.5}$ for low-mass dense cores (Willaims+98)
- [e$^-$] ~ $10^{-6.9-7.3}$ for high-mass dense cores (Bergin+99)

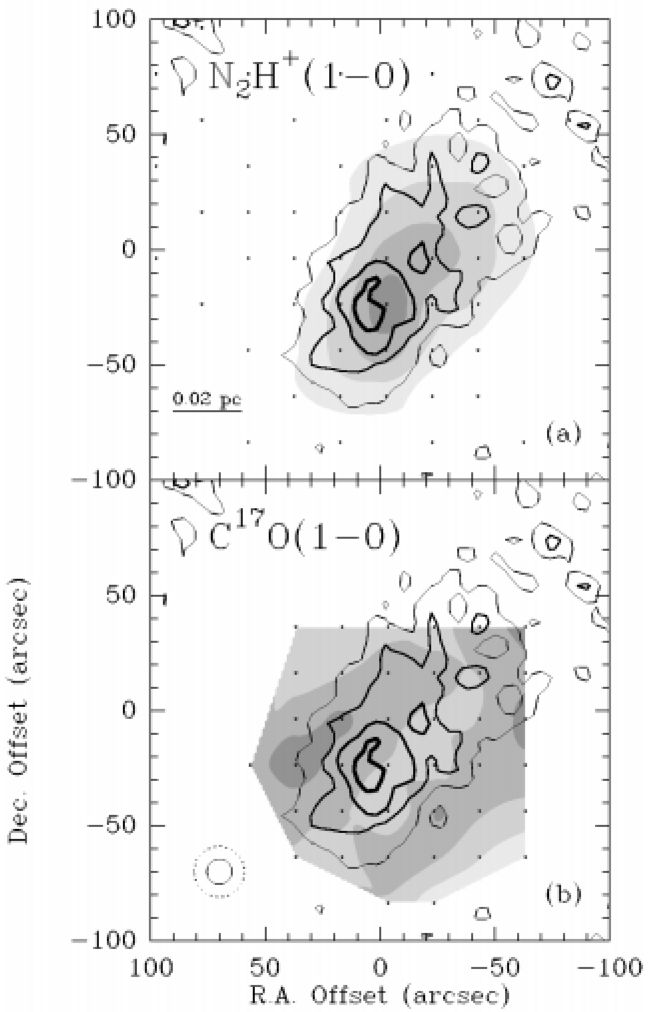
- This method cannot be apply to cold dense cores



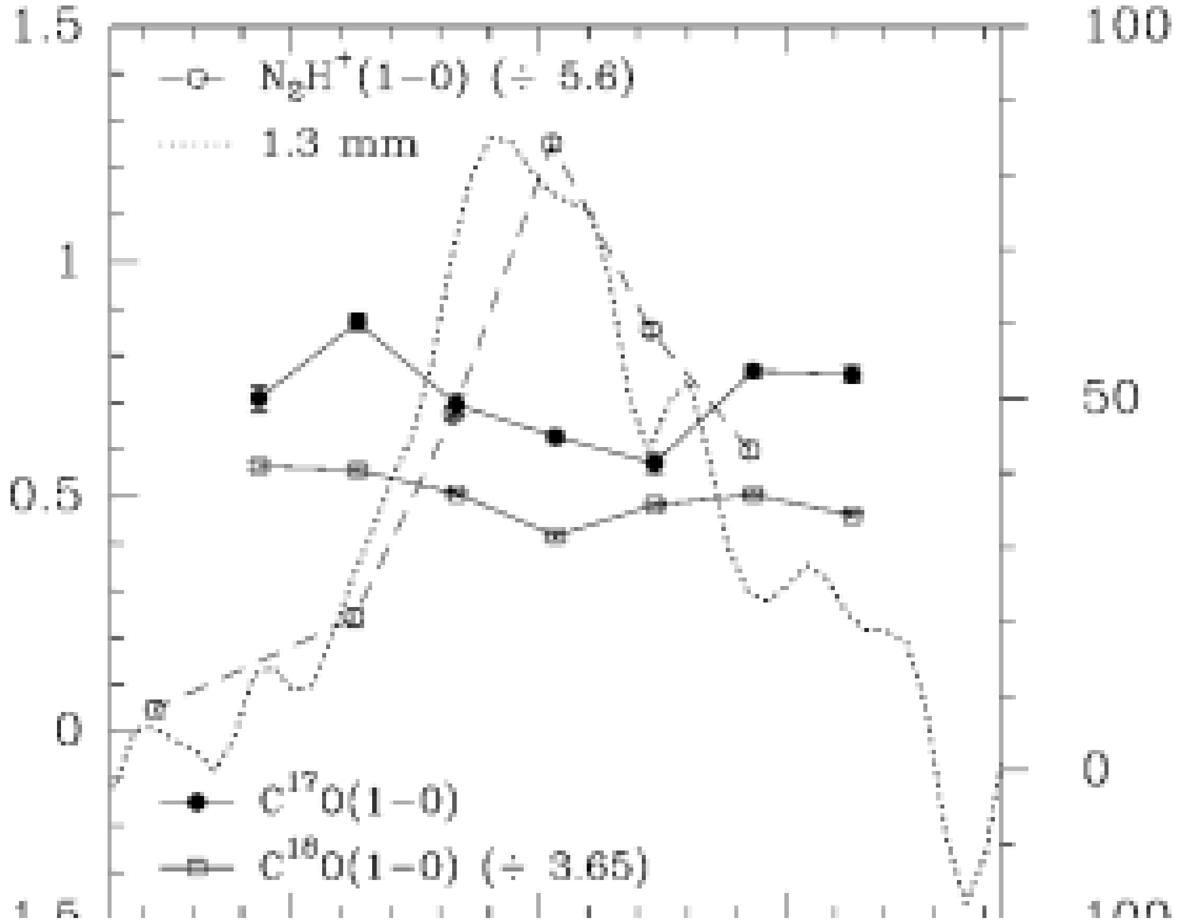


Williams+1998

Cold Dense Cores: Depletion

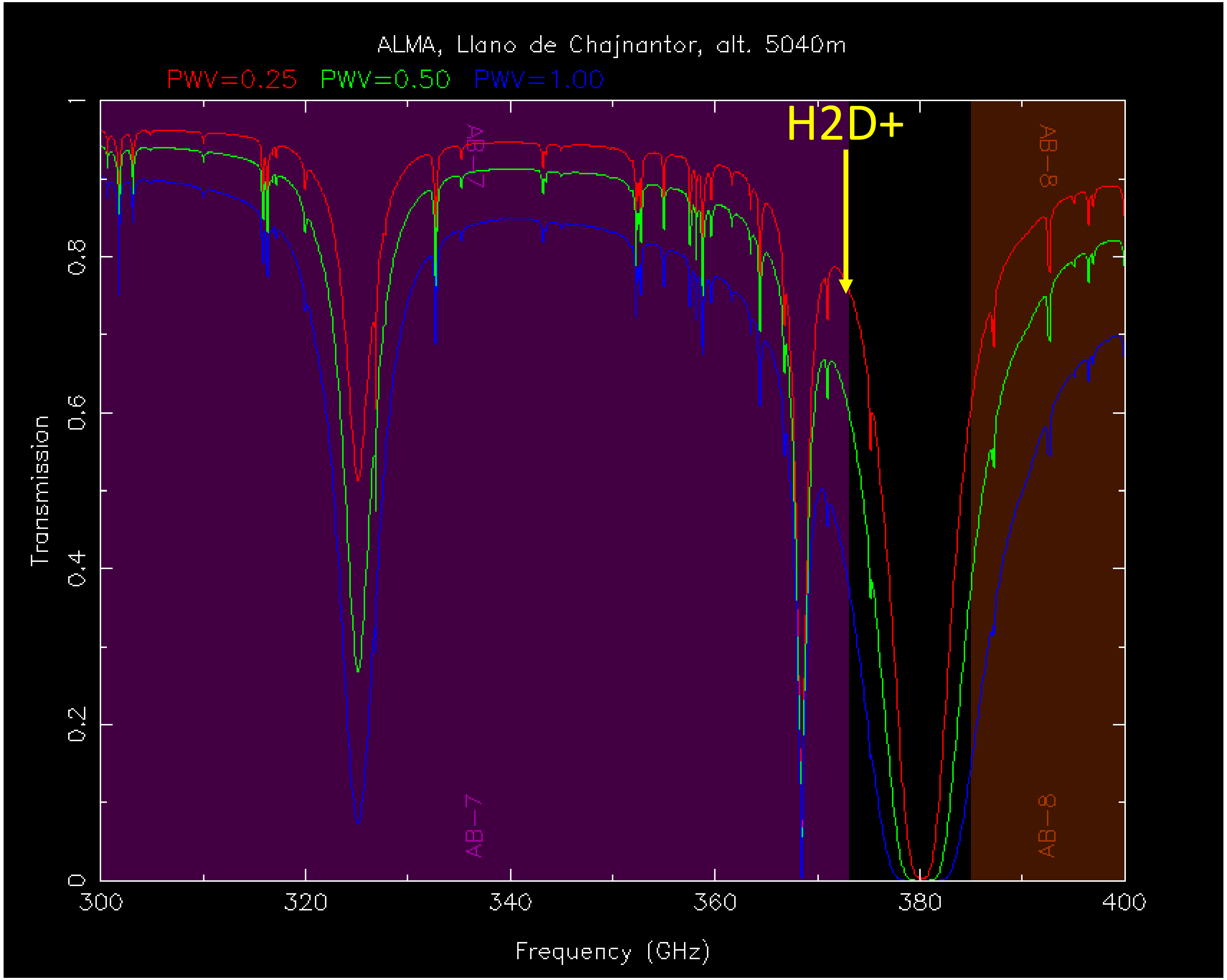


Caselli+99



Measurement of Ionization Fraction: H_2D^+

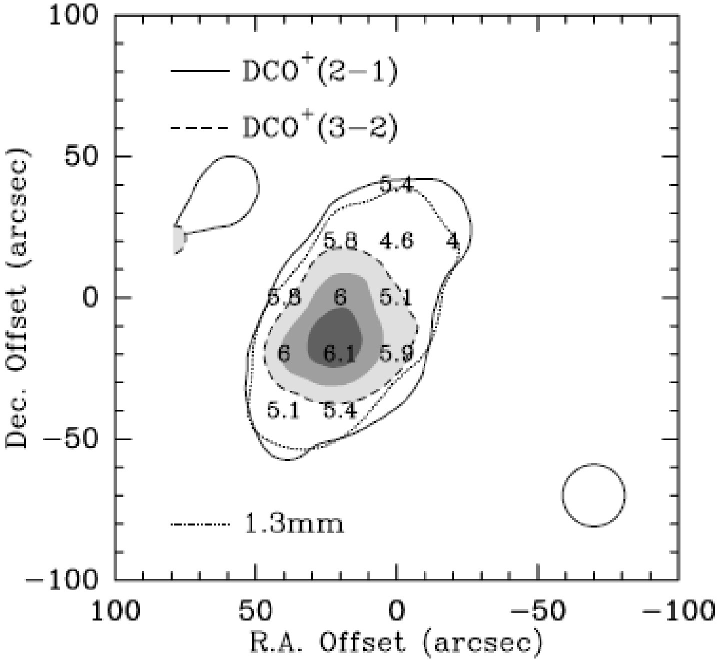
- H_2D^+ is a more direct probe of ionization fraction.
- H_2D^+ is more robust against depletion in dense cold cloud cores.
- It is not easy to observe at 372.421 GHz from ground based telescopes.

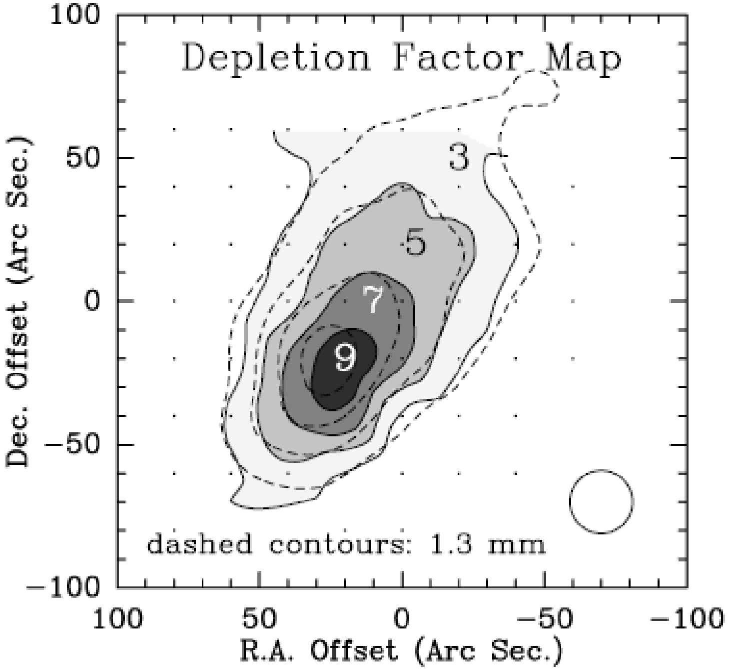

ALMA, Llano de Chajnantor, alt. 5040m
PWV=0.25
PWV=0.50
PWV=1.00
AB-7
AB-7
AB-8
AB-8
Transmission
0
0.2
0.4
0.6
0.8
1
300
320
340
360
380
400
Frequency (GHz)

H2D+

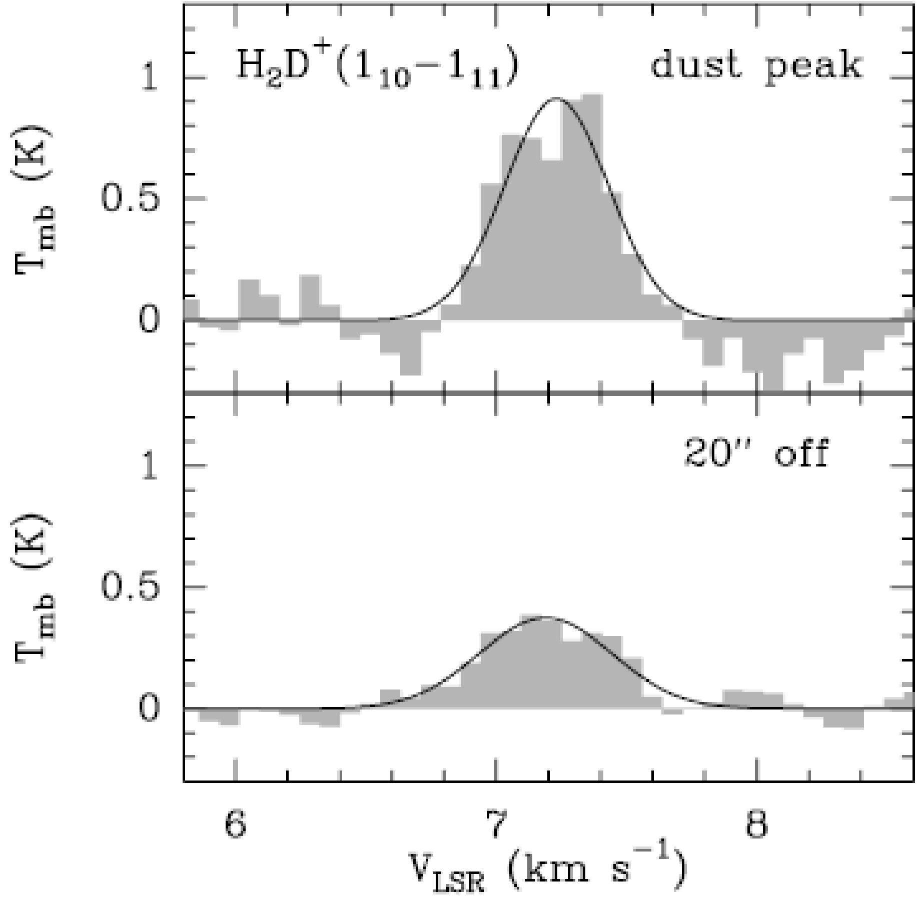
Measurement of Ionization Fraction: H_2D^+

- L1544: low-mass prestellar core





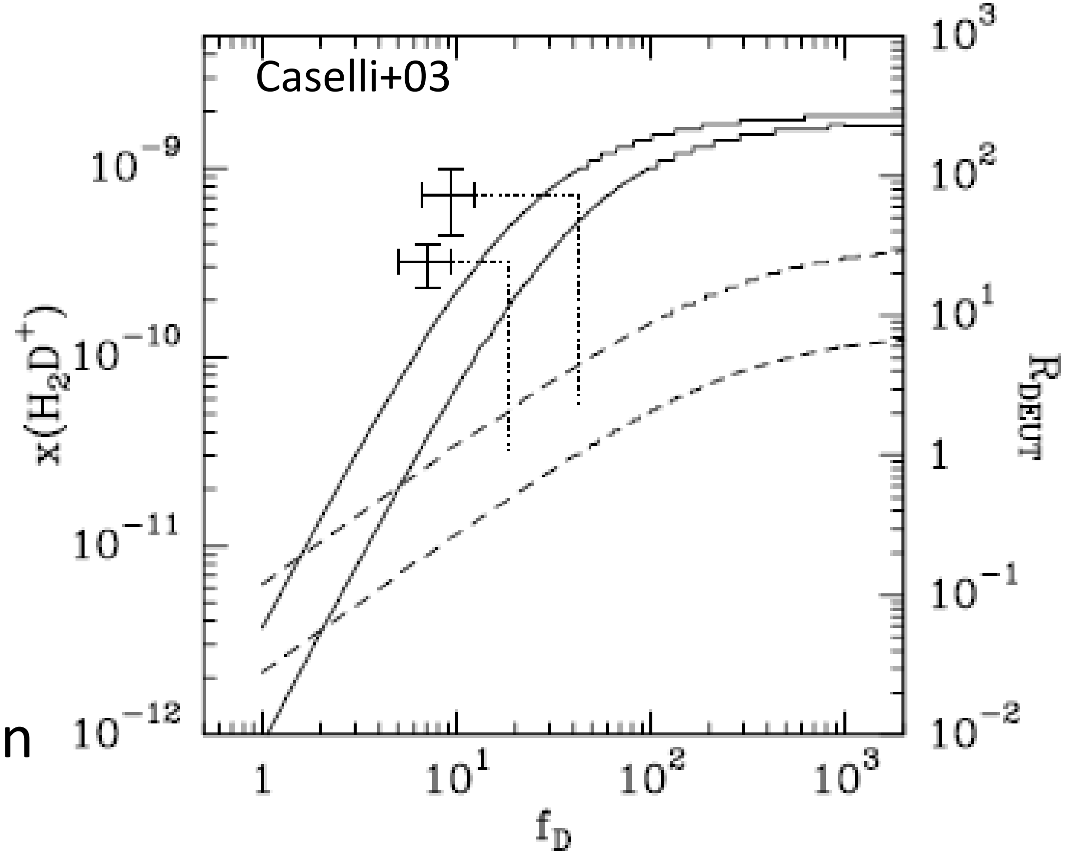
Caselli+03



Measurement of Ionization Fraction: H_2D^+

- $x(H_2D^+)=N(H_2D^+)/N(H_2)$ ~$1x10^{-9}$
- x(e) ~ 2 x 10^{-9}
- $x(H_2D^+)$ ~ x(e)

- Applicable to cold dense cores (IRDC) or dead zone.



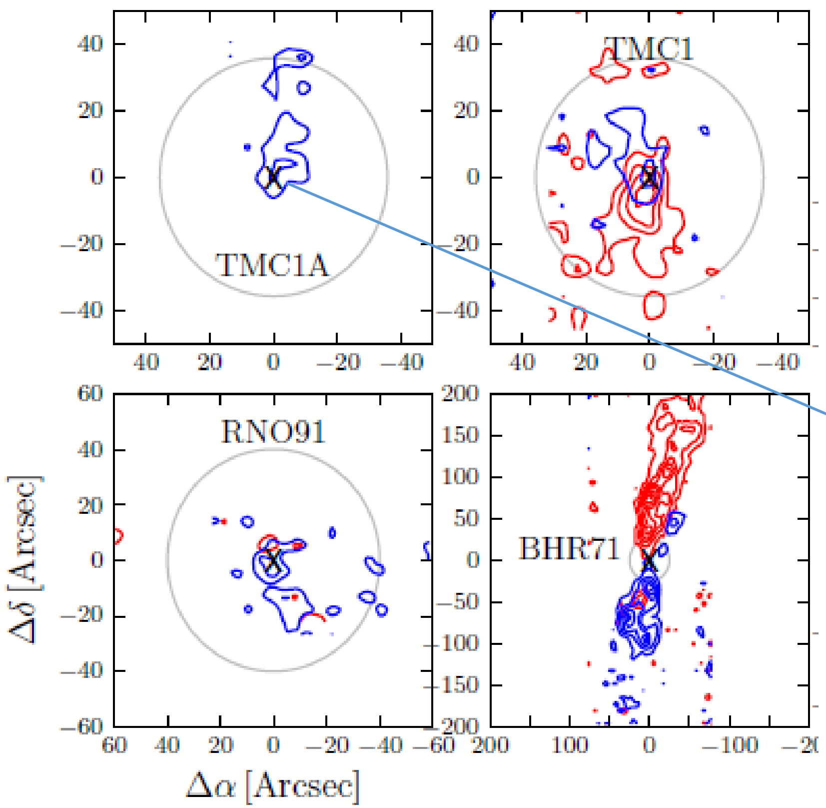
fD: CO depletion factor

$$R_{\mathrm{DEUT}} \equiv \frac{x(\mathrm{H_2D^+})}{x(\mathrm{H_3^+})}$$

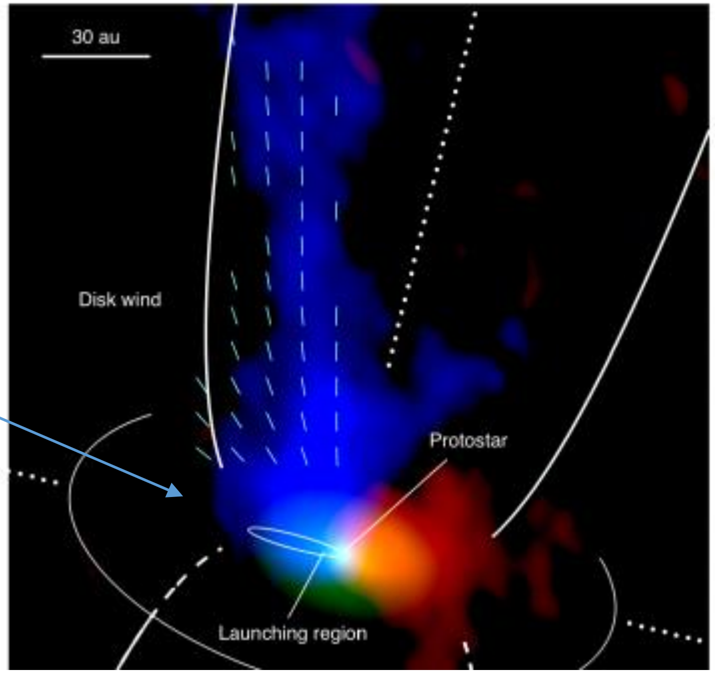
Outflow

Outflow components

- Molecular
  - CO
  - HCO^+
  - H_2
- Atomic
  - HI
  - [C I]
- Ionized
  - [N II]



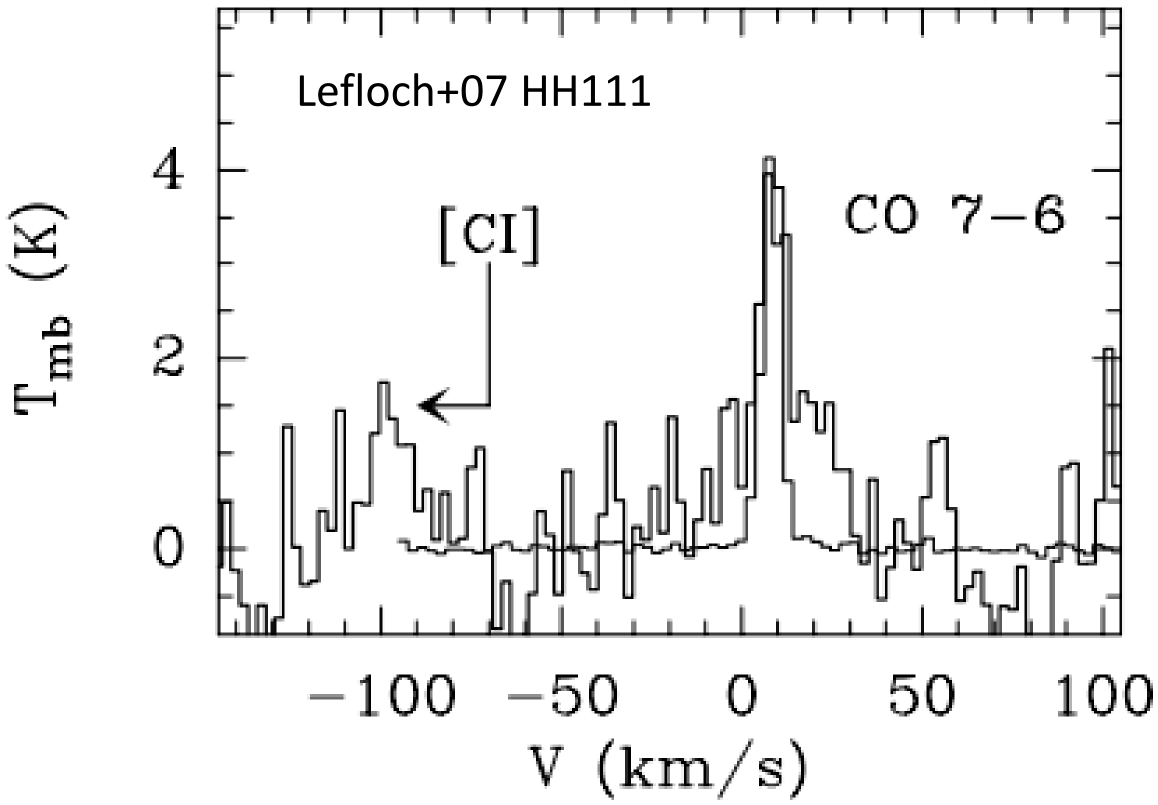
Yıldız+15 CO(6-5) with APEX



Bjerkeli+16

Atomic and Molecular Component

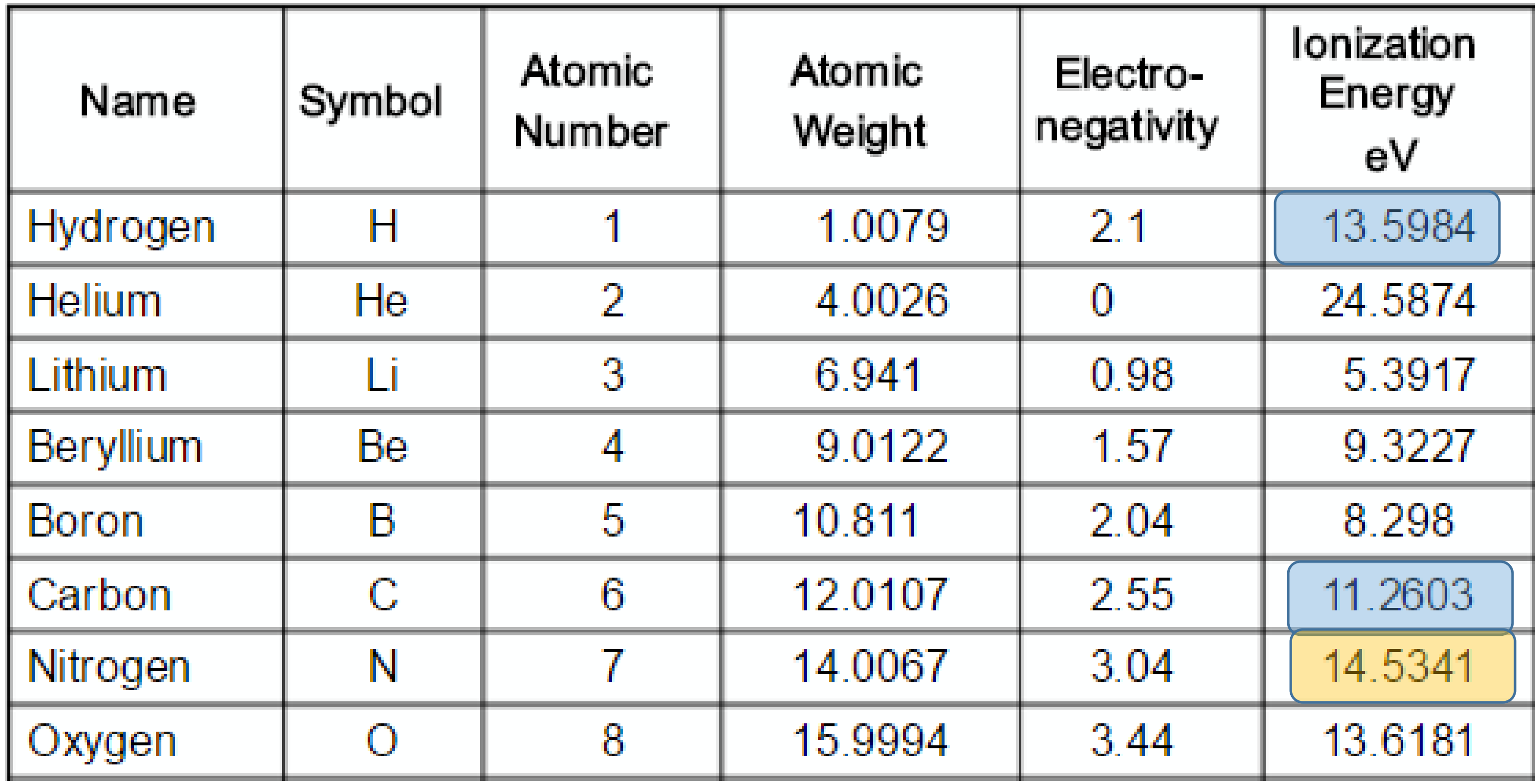
- Spatial Distribution
- Momentum
- Only few [C I] observatio



Ionized Gas

Ionized Gas

- [H II]
  - Halpha
  - Recombination Lines
- [C II]
  - PDR
  - Coexist with H
- [N II]
  - > 13.6 eV
  - Hard tracer



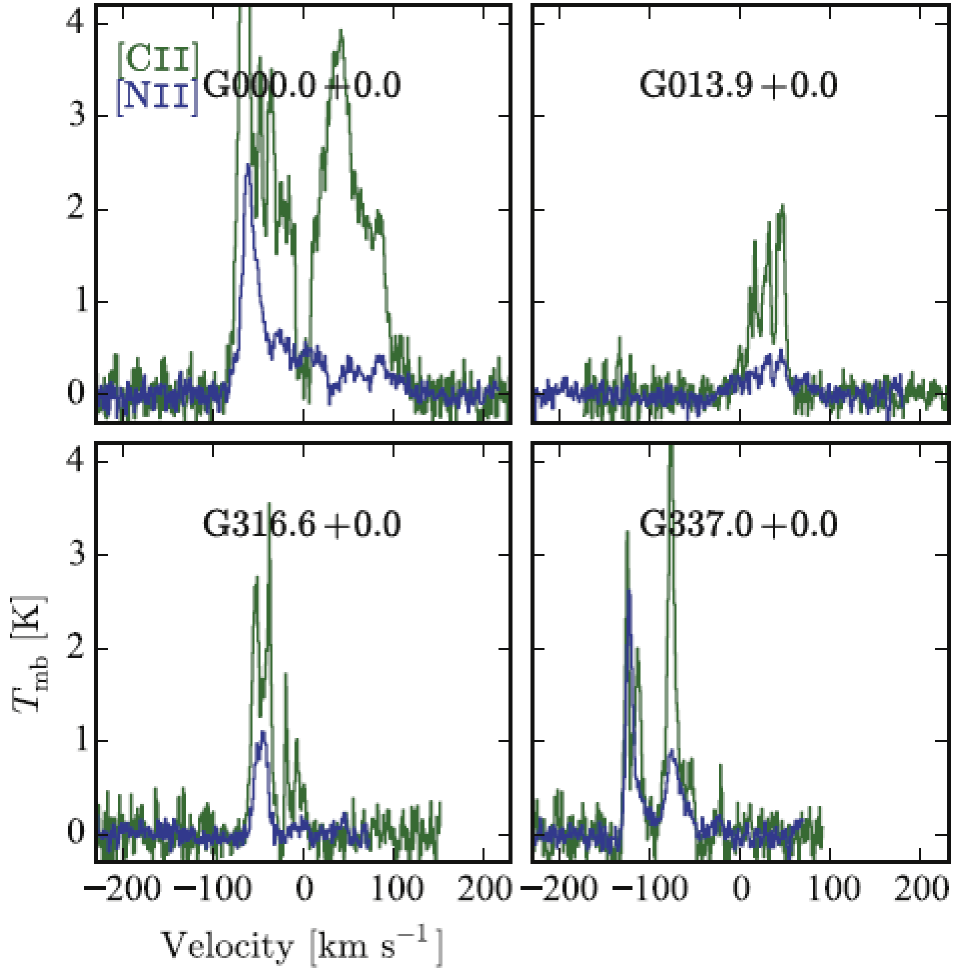
Name	Symbol	Atomic Number	Atomic Weight	Electro-negativity	Ionization Energy eV
Hydrogen	H	1	1.0079	2.1	13.5984
Helium	He	2	4.0026	0	24.5874
Lithium	Li	3	6.941	0.98	5.3917
Beryllium	Be	4	9.0122	1.57	9.3227
Boron	B	5	10.811	2.04	8.298
Carbon	C	6	12.0107	2.55	11.2603
Nitrogen	N	7	14.0067	3.04	14.5341
Oxygen	O	8	15.9994	3.44	13.6181

[N II]

- Exclusively trace (embedded) young massive star, not the warm ionized medium
- Template for extragalactic objects

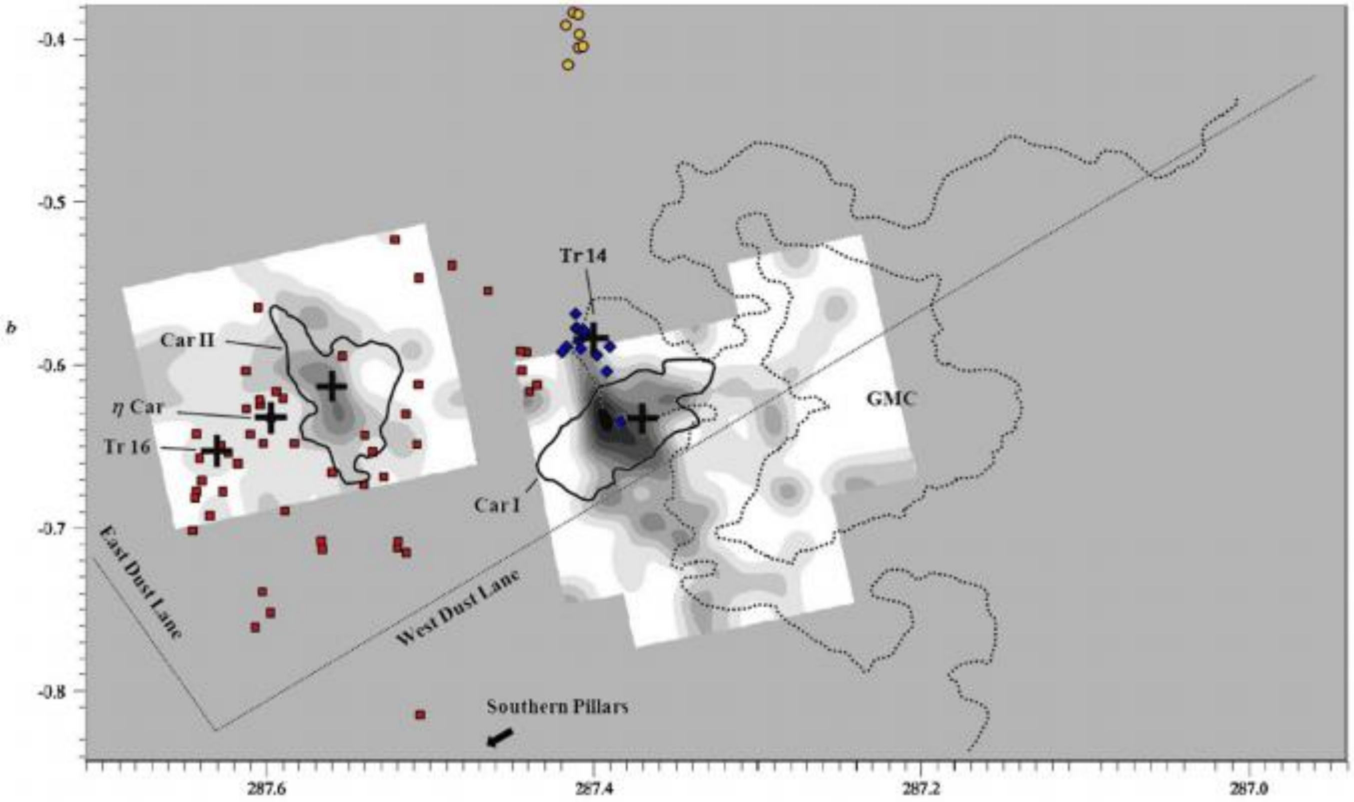
- Applicable to jet/outflow or protoplanetary disk?

Goldsmith+15



[N II] map of Carina

- Corresponds to ionized region
- Trace extended Low-density (ELD) ionized region.



Oberst+11 with SPIFI

Proposed Observations

H_2D^+ Targets

- Goal: To derive x(e) in dense cold cores at pre-stellar phase
- $A_v \gtrsim 10$ mag., or N(H) $\gtrsim 5.8 \times 10^{21}$ cm^{-2} & cold ($T \approx 10K$) regions (to be complimentary to near-IR and SPICA), Low-mass prestellar cores and/or IRDCs
- Same targets as Momose-san’s talk
- $dT_A^* = 0.3$ K in TB
- $d\nu = 0.25$ km/s
- Mapping area 120” with 2” sampling
- Obstime ~ 60/4 x 60 x 60 x 3 sec ~ 45 hr

[C I]/CO(7-6) Targets

- Goal: To derive momentum of atomic component of young outflows
- Low-mass Protostars
- dT_A^* = 0.54 K in TB
- $d\nu$ = 1 km/s
- Mapping area 120” with 1” sampling
- Obstime ~ 120/4 x 120 x 30 x 3 sec ~ 180 hr

[N II] Targets

- Goal: To reveal spatial distribution of hardness of ionization
- Cluster Regions
- dT_A* = 2 K in TB
- dν = 1 km/s
- => dt = 45 sec
- Mapping area 70” with 0”.7 sampling
- Obstime ~ 100/4 x 100 x 45 x 3 sec ~ 94 hr

System Requirement

- Antenna ([N II] Observable at 1.5 THz)
  - Pointing (<1/10 θ_{FWHM}) – overcoming disturbance and pointing jitter
  - Surface accuracy (< 16/$\lambda \sim 12$ μm)
- Rx
  - Frequency Coverage (373 GHz observable (currently at band edge?)
  - Sideband Rejection (> 10 dB) – Avoid noise from an imaging band
  - IF bandwidth (> 10 GHz) CO/[C I] obs with HCO^+
  - Spectral dynamic range
  - Gain Stability
- Data Storage

1.5 THz with 3.5 GHz width ~ 115 GHz with 250 MHz

Calibration Requirement

- Amplitude Calibration (not established > 1 THz)
  - Absolute
  - Relative (repeatability)
- Pointing/squint/focus
  - Pointing jitter?
- Surface/Efficiency

Summary

- Star Formation Study with the 30 m telescope
- Ionization fraction (H_2D^+)
- Atomic/molecular outflow ([C I]/CO)
- [N II] observations
- System requirements to be considered accordingly

- Each science topic in the present talk is to be compared against other methods in detail.