星間化学における
テラヘルツ単一鏡観測の役割

テラヘルツ領域の輝線

@Herschel, CSO…

<u>高励起（高臨界密度）ライン</u>

$\because E(J+1)\text{-}E(J)=2hcB(J+1)$

$A_{21} \propto \nu^3$

⇒ 星形成コア中心部の化学

<u>Hydrates</u>

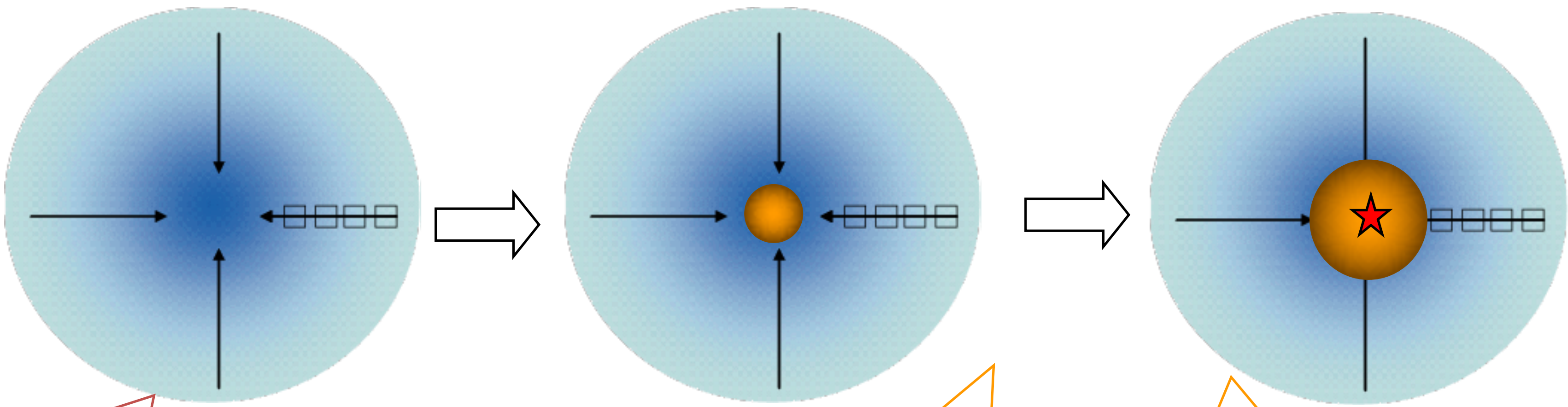
- H_2D^+ & D_2H^+
- CH^+
- OH^+
- Cl

⇒重水素の化学

⇒ Diffuse cloud と分子雲形成

星形成領域の化学

◎気相反応と固相の相互作用
◎固相の詳細な組成は昇華物を観るしかない

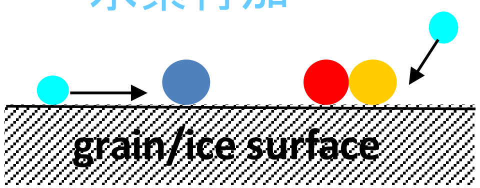


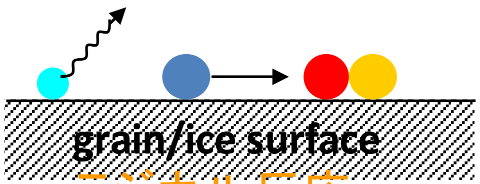
ダスト表面への分子凍結
水素付加
e.g. $CO \rightarrow CH_3OH$
$T < 20K$

熱拡散による
ダスト表面反応
$20K < T < 100K$

昇華分子同士の気相反応
$T > 100K$

水素付加





ラジカル反応

分子種	昇華温度[K]
H_2CO	39–52
CO_2	50–68
CH_3OCH_3	59–80
C_2H_6	83–110
CH_3O	96–130
CH_3OH	100–140
NH_3	100–140
H_2O	110–150
$HCOOCH_3$	120–160

@ $n_H = 10^6\text{-}10^{12} cm^{-3}$

Furuya & YA (2014)

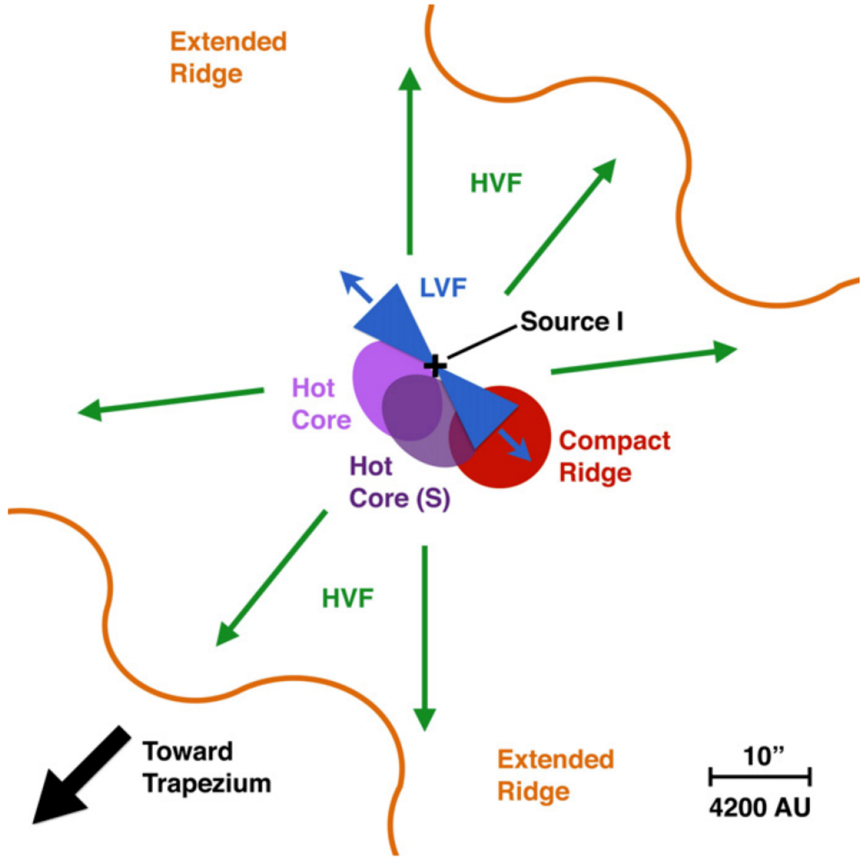
Garrod & Herbst (2006); Aikawa et al. (2008)

HEXOS (Herschel/HIFI Observations of EXtraOrdinary Sources)

(Crockett et a. 2014; 2015)

◎39分子種（79同位体種）からの~13000本のラインを検出
◎Spectral feature (v_{lsr}, dv)のfitでhot core, compact ridge, plateau , extended ridgeを切り分け
◎N-bearing, S-bearingの輝線はO-bearingよりも高温領域から放射

空間分解能
Herschel 44”@480GHz, 11”@1900GHz
(cf. 南極10m 17”@460GHz, 5.7”@1300GHz)



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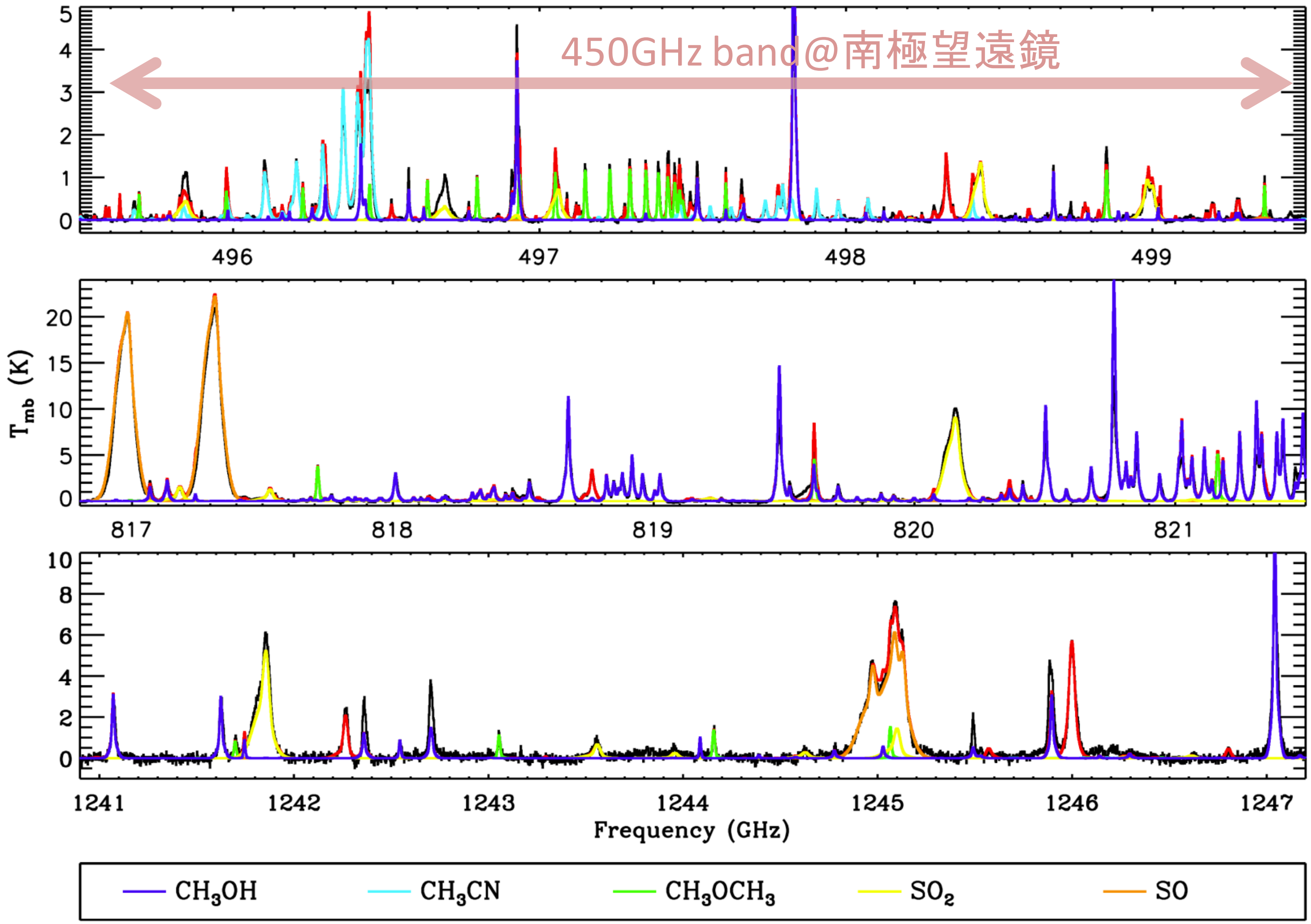

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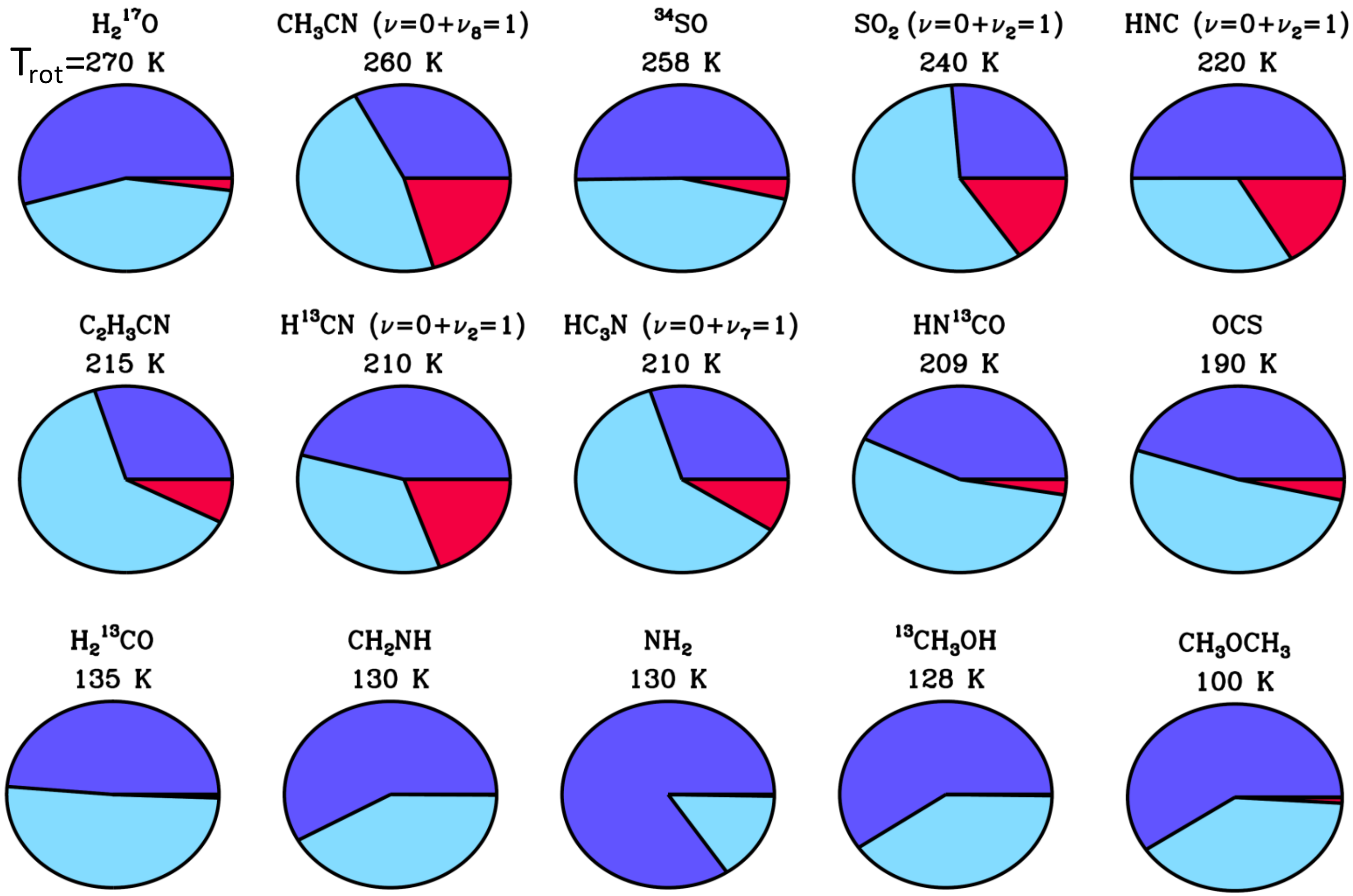
E_{up}=0-200 K

E_{up}=200-800 K

E_{up}=800-3000 K



Fraction of total integrated intensity originating states in Eup

重水素濃縮とo/p比

- Exothermic exchange reactions

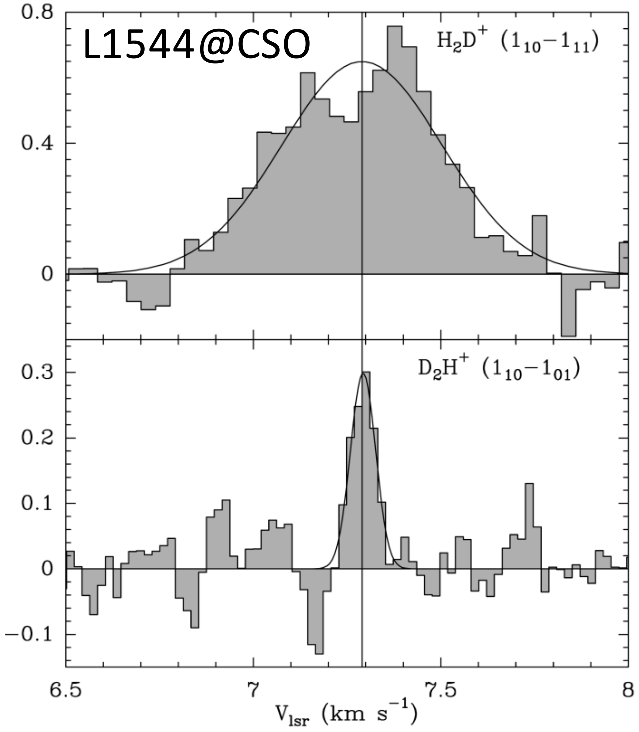
$$H_3^+ + HD \underset{\times}{\rightleftarrows} H_2D^+ + H_2 + \Delta E$$

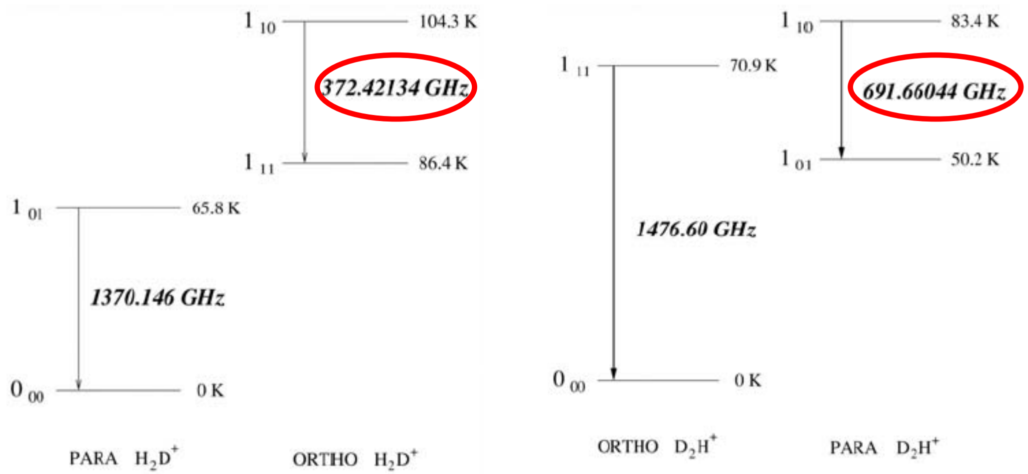
- High D/H propagates to other molecules via reactions
  - $X + H_2D^+ \rightarrow XD^+ + H_2$ (1/3)
  - $XH^+ + HD$ (2/3)

- $H_2D^+ + e \rightarrow H_2 + D$

on ice: $D + X \rightarrow DX$

H_2D^+, D_2H^+にはオルソ・パラが存在。
→H_2D^+/H_3^+比などの測定にはオルソ・パラ両方の観測が必要





Stark et al. 1999
Caselli et al. 2003
Vastel et al. 2006

重水素濃縮とo/p比

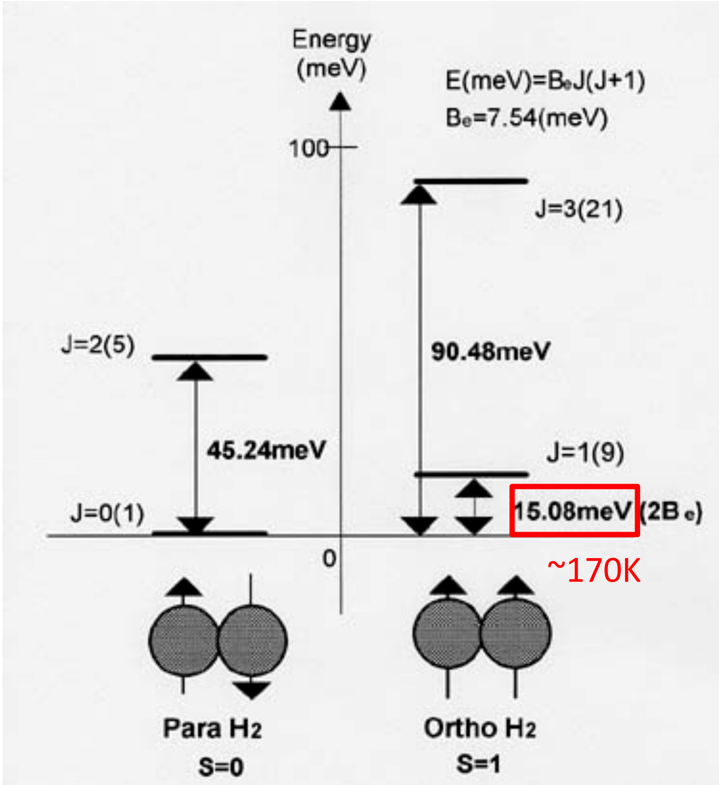
- Exothermic exchange reactions

$$H_3^+ + HD \underset{\times}{\rightleftarrows} H_2D^+ + H_2 + \Delta E$$

H2, H_2D^+のo/p比に依る

H_2D^+のオルソ・パラ比
⇔H_2のオルソ・パラ比

$$\text{p-}H_2D^+ + \text{p-}H_2 \rightarrow \text{o-}H_2D^+ + \text{o-}H_2 - 257\ \mathrm{K},$$
$$\text{p-}H_2D^+ + \text{o-}H_2 \rightarrow \text{o-}H_2D^+ + \text{o-}H_2\ (\text{p-}H_2) - 87\ (+83)\ \mathrm{K},$$
$$\text{o-}H_2D^+ + \text{p-}H_2 \rightarrow \text{p-}H_2D^+ + \text{o-}H_2 - 83\ \mathrm{K},$$
$$\text{o-}H_2D^+ + \text{o-}H_2 \rightarrow \text{p-}H_2D^+ + \text{p-}H_2\ (\text{o-}H_2) + 257\ (+87)\ \mathrm{K}.$$



- H_2のo/p比は生成時は3
  --> 気相反応により変化

$$H + H \longrightarrow \begin{cases} \text{o-}H_2 & 75\% \\ \text{p-}H_2 & 25\% \end{cases}$$

(Watanabe et al. 2010)

$$\text{o-}H_2 + XH^+ \rightarrow \text{p-}H_2 + XH^+$$
$$\text{p-}H_2 + XH^+ \rightarrow \text{o-}H_2 + XH^+$$

重水素濃縮とo/p比

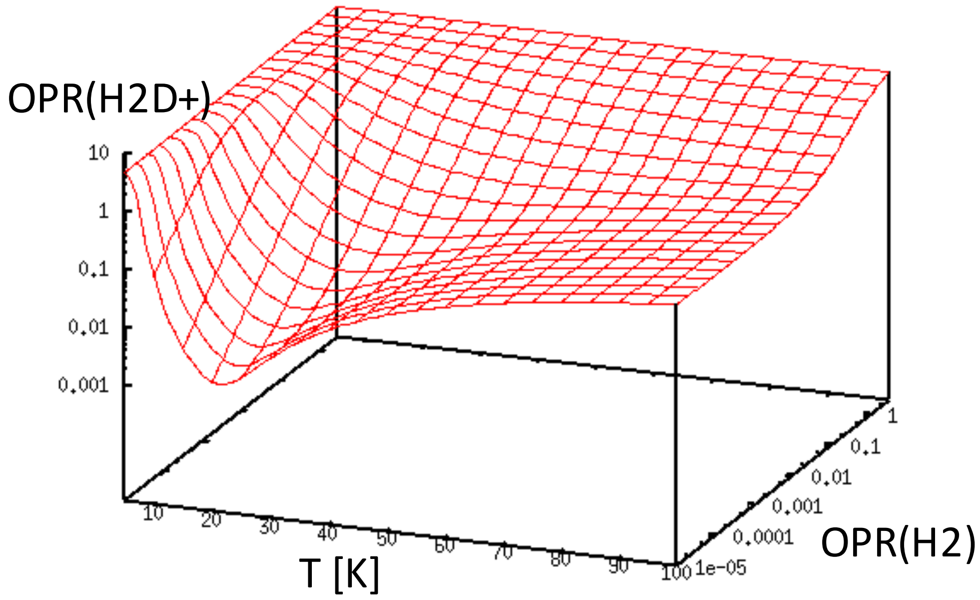
Exothermic exchange reactions

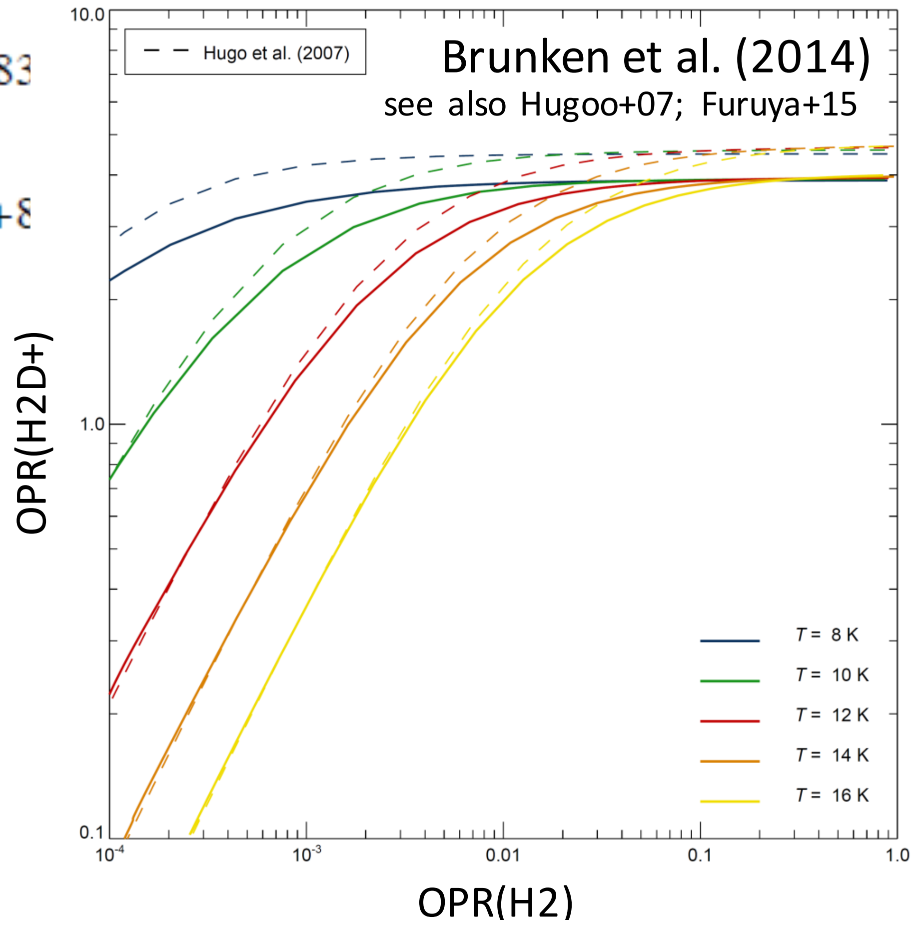
$$H_3^+ + HD \underset{\times}{\rightleftarrows} H_2D^+ + H_2 + \Delta E$$

H_2, H_2D^+のo/p比に依る

H_2D^+のオルソ･パラ比
⇔H_2のオルソ･パラ比

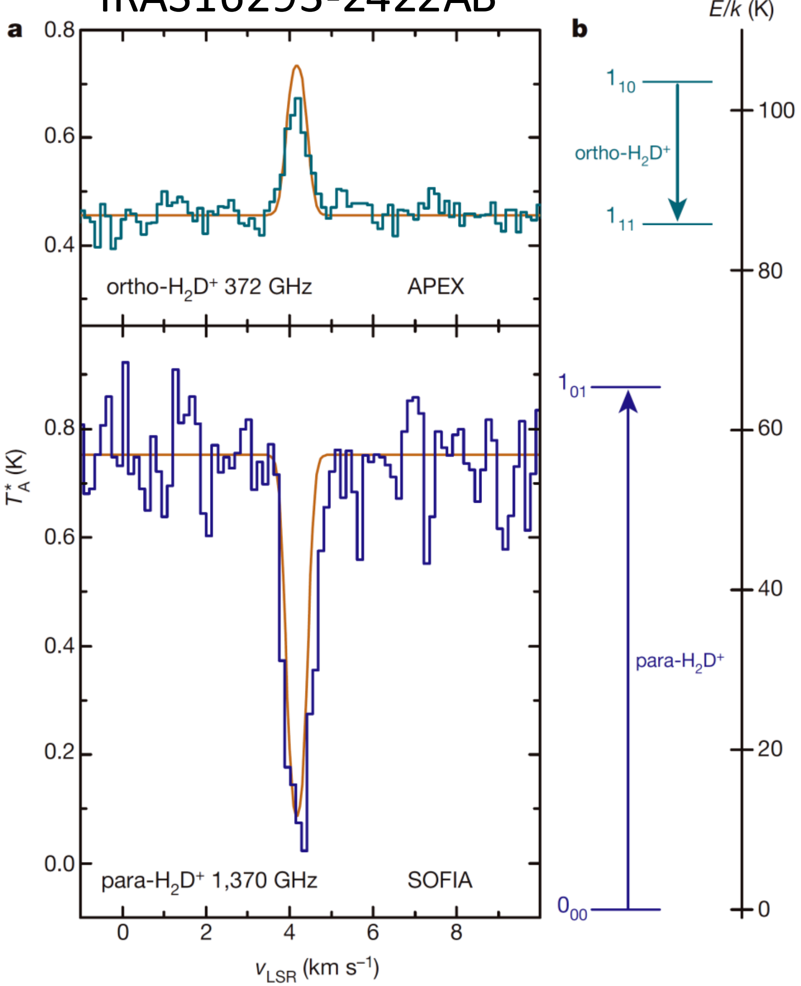
$$\text{p-}H_2D^+ + \text{p-}H_2 \rightarrow \text{o-}H_2D^+ + \text{o-}H_2 - 257\ \text{K},$$
$$\text{p-}H_2D^+ + \text{o-}H_2 \rightarrow \text{o-}H_2D^+ + \text{o-}H_2\ (\text{p-}H_2) - 87\ (+83$$
$$\text{o-}H_2D^+ + \text{p-}H_2 \rightarrow \text{p-}H_2D^+ + \text{o-}H_2 - 83\ \text{K},$$
$$\text{o-}H_2D^+ + \text{o-}H_2 \rightarrow \text{p-}H_2D^+ + \text{p-}H_2\ (\text{o-}H_2) + 257\ (+8$$





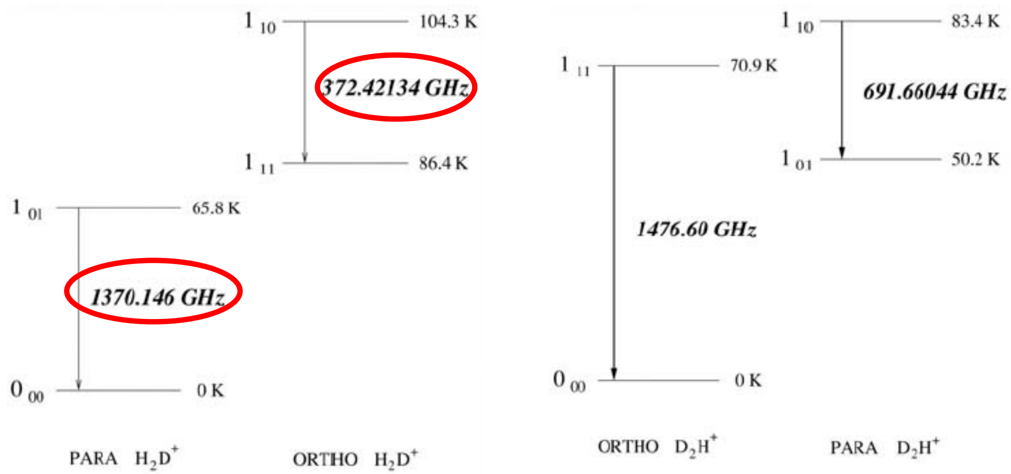
重水素濃縮とo/p比

IRAS16293-2422AB



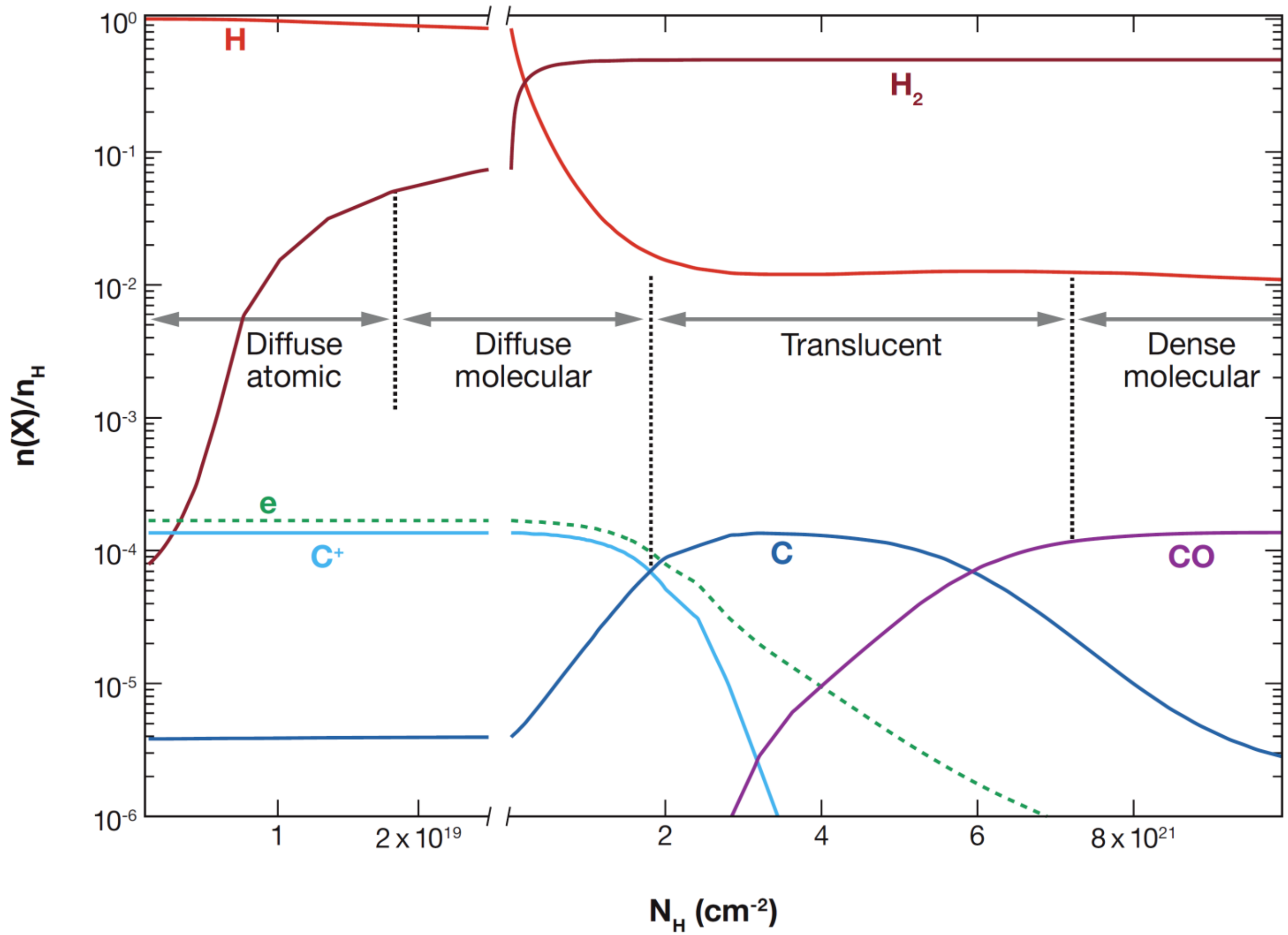
$OPR(H_2D^+)=0.07\pm 0.03$

$\text{-->}\ OPR(H_2) \sim 2\text{x}10^{-4}$



Brunken et al. (2014)

Diffuse cloudと分子雲形成



- H_2 fraction
- HCO^+, C_2H, C_3H_2…
- Ionization rate
- CH^+の化学
- CI

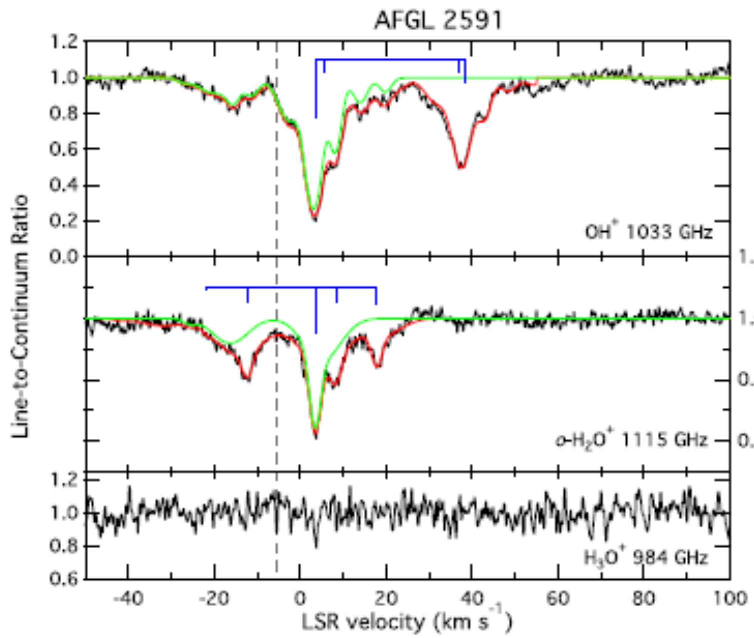
	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n{}_{H_2} < 0.1$	$f^n{}_{H_2} > 0.1$ $f^n{}_{C+} > 0.5$	$f^n{}_{C+} < 0.5$ $f^n{}_{CO} < 0.9$	$f^n{}_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

Snow & McCall (2006)

H_2 fraction and ionization rate

OH^+@900GHz, 1030GHz
H_2O^+@600GHz
H_3O^+@986GHz

H_2 fraction とイオン化率（宇宙線）の指標



H + cr → H^+ + e + CR'
H^+ + O + 226K ← → O^+ + H
O^+ + H_2 → OH^+ + H
OH^+ + H_2 → H_2O^+ + H

$$f_{H_2} = \frac{2x_e k_7/k_4}{N(OH^+)/N(H_2O^+) - k_6/k_4},$$

$$\epsilon\zeta_H = \frac{N(OH^+)}{N(H)} n_H x_e \left[\frac{k_7}{N(OH^+)/N(H_2O^+) - k_6/k_4} + k_5\right].$$

f_{H2}=0.042+0.018
ζ_H=(1.78+0.29)x10^{-16} s^{-1}

Indriolo et al. (2015)

CH^+ in diffuse clouds

CH^+@835GHz

$^{13}CH^+$@830GHz

SH^+: 526GHz

shockや乱流によるkinetic
エネルギーの散逸を利用？

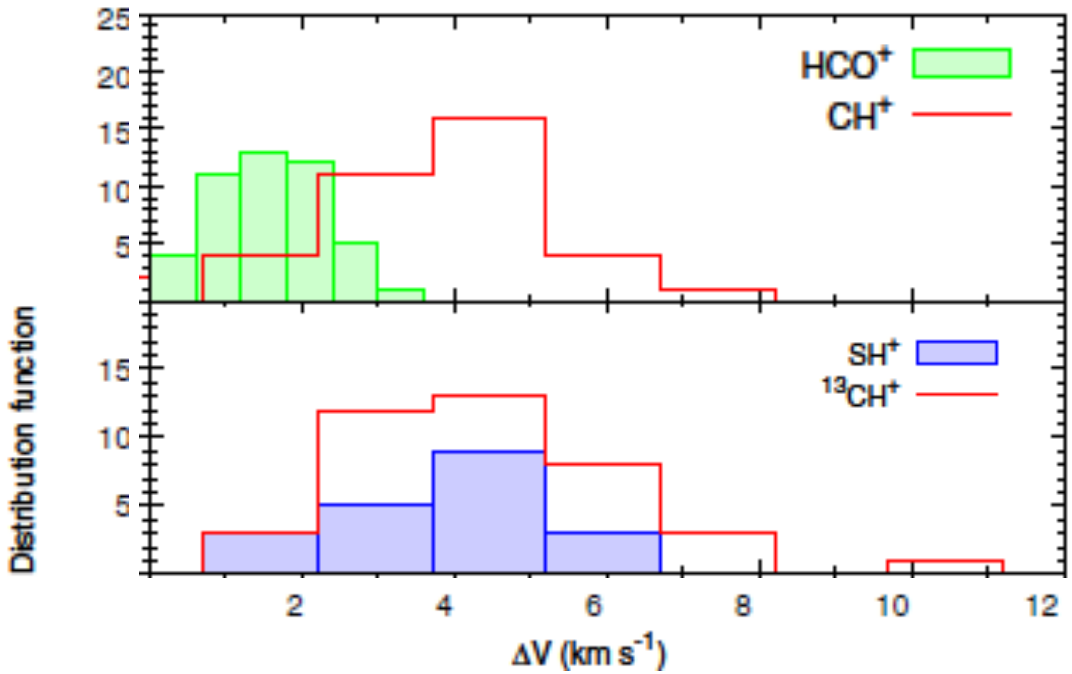
$$C^+ + H_2 \rightarrow CH^+ + H \quad \Delta E/k = 4640\ K,$$

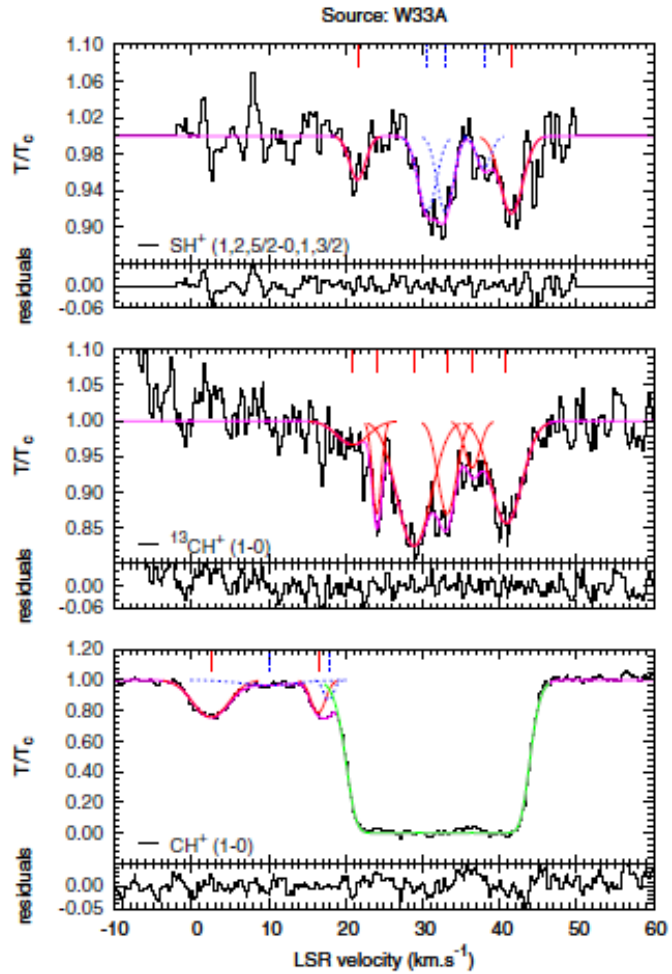
$$S^+ + H_2 \rightarrow SH^+ + H \quad \Delta E/k = 9860\ K.$$

$$CH^+ + H_2 \rightarrow CH_2^+ + H \text{ and}$$

$$SH^+ + e^- \rightarrow S + H,$$

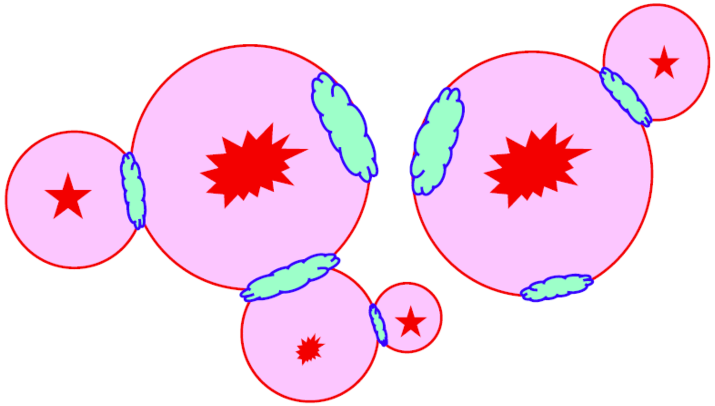
ΔV(HCO+) < ΔV(CH+, SH+)



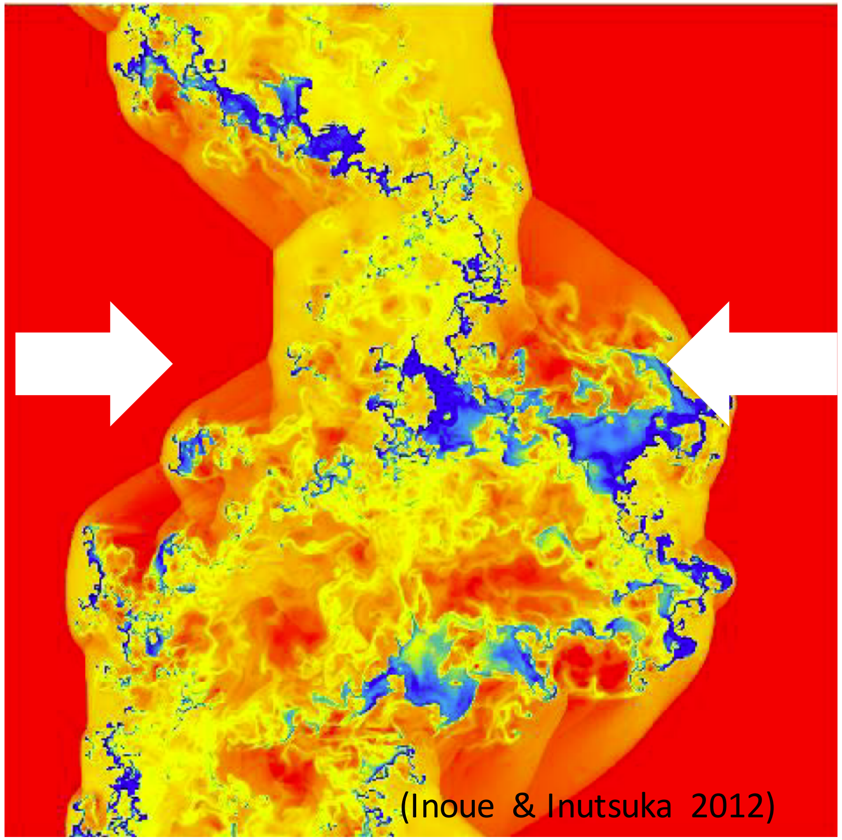


Diffuse cloudと分子雲形成

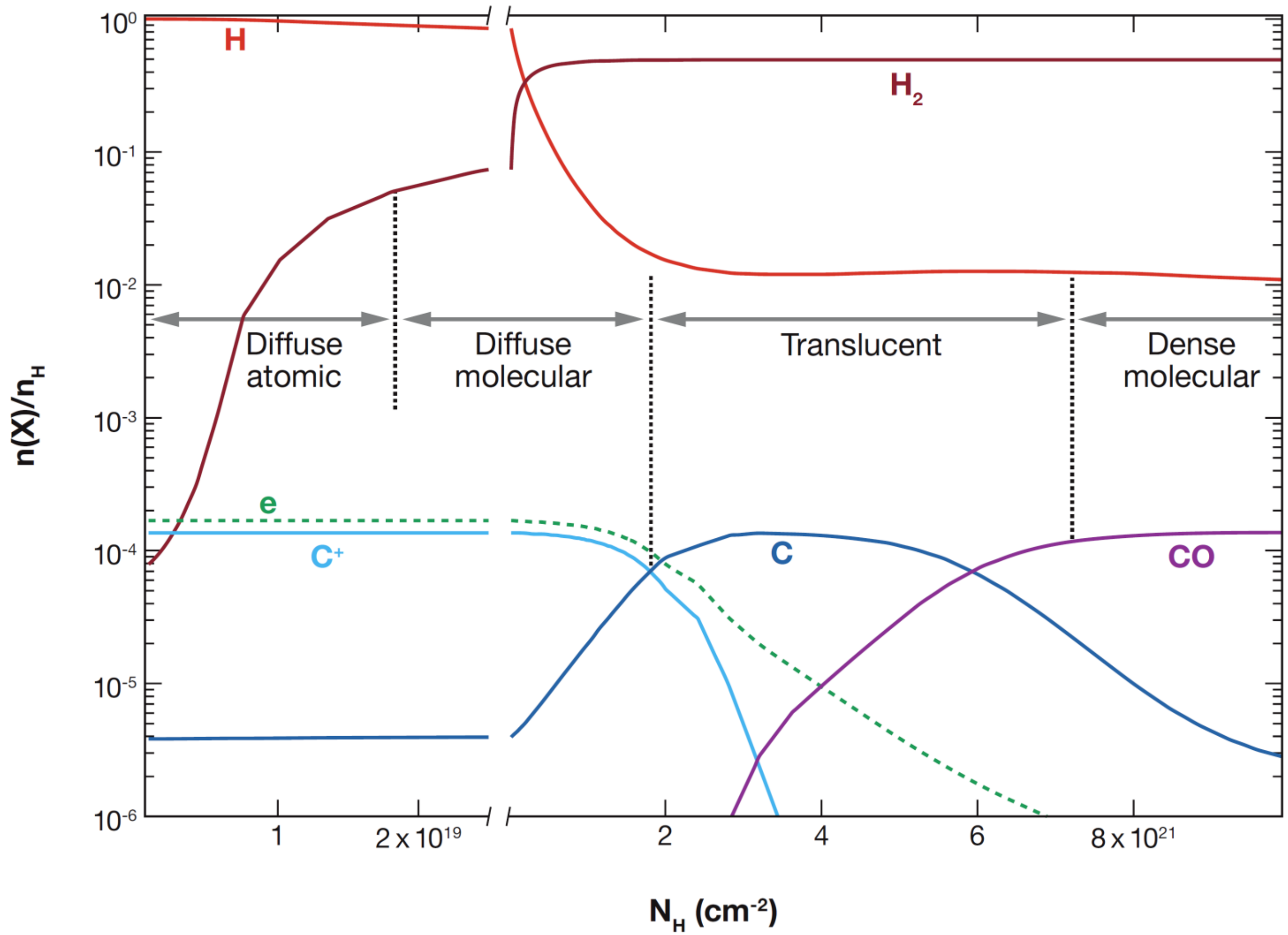
＃分子雲形成は希薄なHIガスの掃き集め
磁場が圧縮を阻害
--> 複数回の掃き集めが必要
(Inoue & Inutsuka 2012; Inutsuka et al. 2015)



Diffuse cloud は「最終掃き集め」前のガス？



Diffuse cloudと分子雲形成



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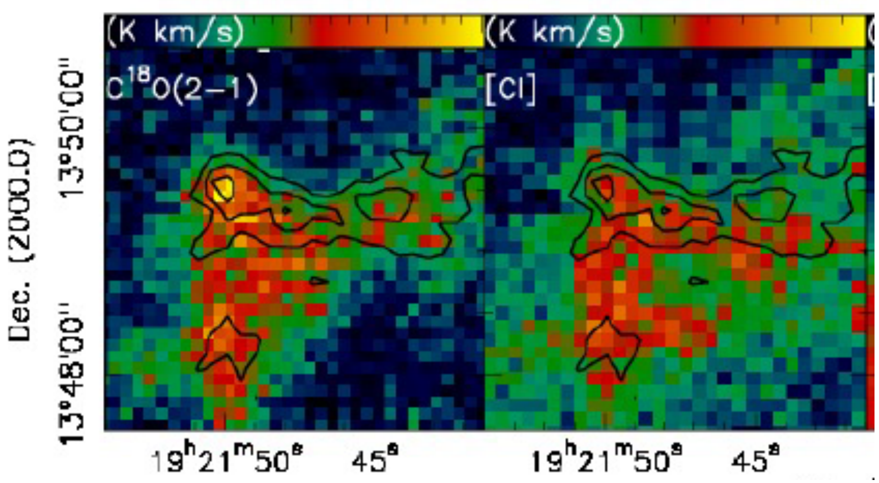
Snow & McCall (2006)

CII/CI/CO in IRDC

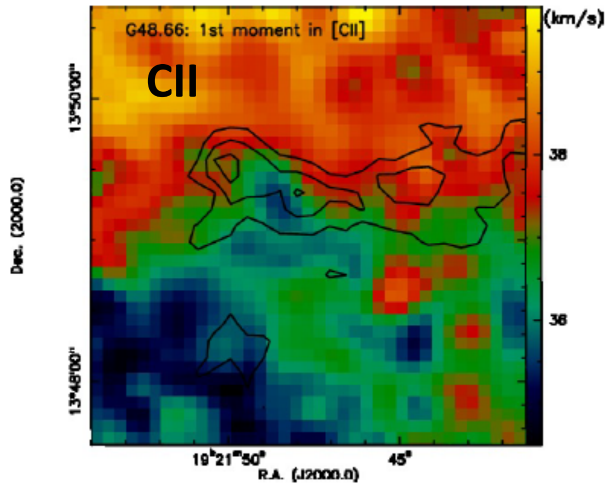
Beuther et al. (2014)

CII@1900GHz (Herschel & SOFIA)
CI@492GHz (APEX)
CO@219GHz (IRAM30m)

G48.66



Intensity-weighted velocity



phase	G11.11 ($M_\odot$)	G48.66 ($M_\odot$)	IRDC18223 ($M_\odot$)	IRDC18454[3] ($M_\odot$)
CO	0.81	0.30	1.84	13.4
[CI]	0.056	0.025	0.21	1.6
[CII]@50K	< 0.012	0.12[1]	0.54	14.8
[CII]@100K	< 0.005	0.05[1]	0.21	5.7
CO/[CI]/[CII]@50*K*	14.5/1/>0.2	12/1/4.8	8.8/1/2.6	8.4/1/3.6[2]
Approx. area of emission (pc^2)[4]	5.2	3.7	6.5	31.4

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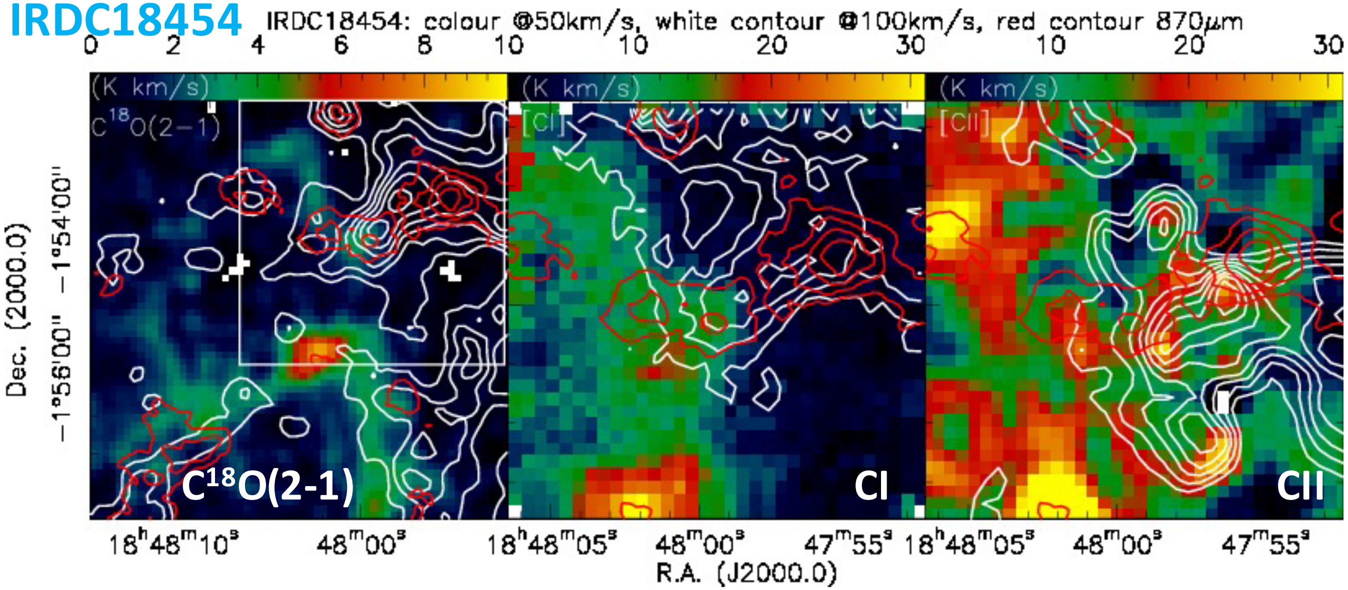
Beuther et al. (2014)

CII@1900GHz (Herschel & SOFIA)
CI@492GHz (APEX)
CO@219GHz (IRAM30m)

IRDC18454



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星間化学における
テラヘルツ単一鏡観測の役割

ALMAで観測できない
（容易でない）周波数

広がった天体

テラヘルツ領域の輝線

@Herschel, CSO…

高励起（高臨界密度）ライン

$\because E(J+1)-E(J)=2hcB(J+1)$

$A_{21} \propto \nu^3$

⇒ 星形成コア中心部の化学

Hydrates

- H_2D^+ & D_2H^+
- CH^+
- OH^+
- CI

⇒重水素の化学

⇒ Diffuse cloud と分子雲形成