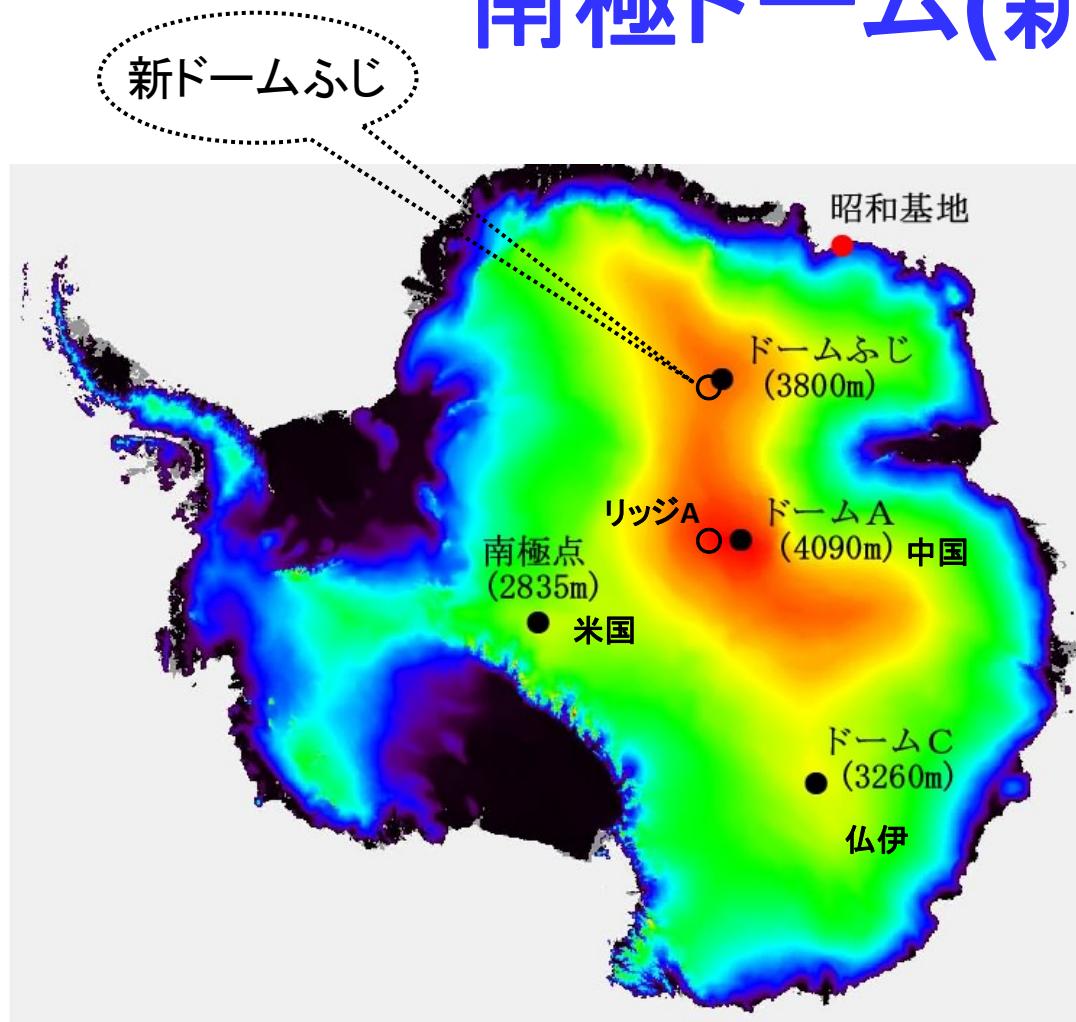


初期宇宙の水素分子の 観測可能性

筑波大学宇宙観測研究室
中井直正

- 南極内陸部高原地帯に望遠鏡を設置予定
- 初期宇宙での初代星・初代銀河の形成過程の
解明のため、水素分子(H_2)の観測はできないか？
星形分子雲は観測不可
銀河形分子は？

南極ドーム(新)ふじ基地



↗ ~1000 km

地理的標高 3800 m
気温

最高	-20 °C
平均	-54 °C
最低	-80 °C



大気中の水蒸気が極めて少ない



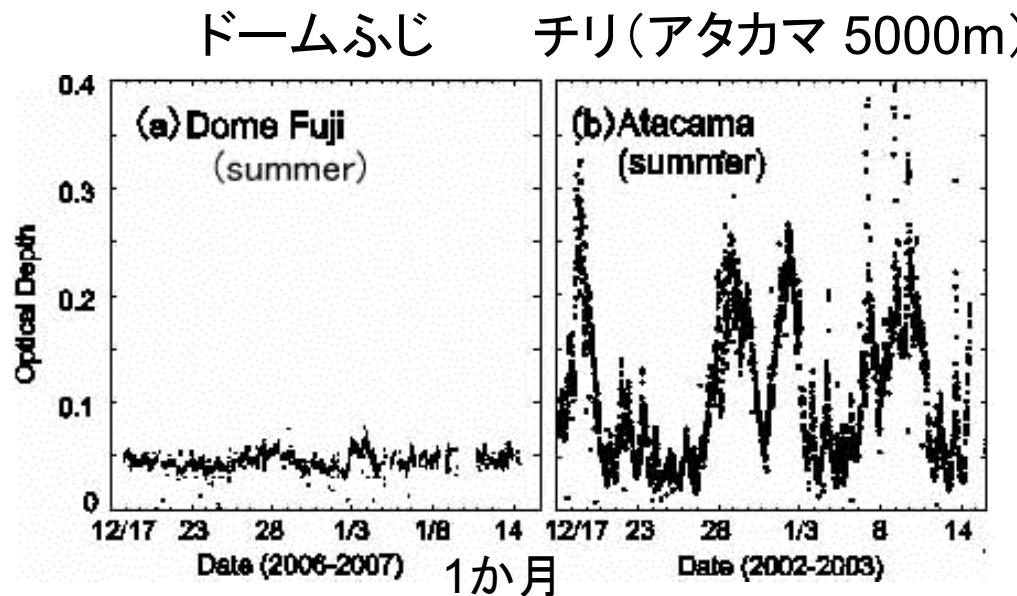
サブミリ、テラヘルツ、赤外線の
観測環境が地上で最高

緯度 = S77度
観測可能: 赤経 $< +3^\circ$ at EL > 10°

大気透過率

220 GHz@ドームふじ 実測： 2006,09年夏季

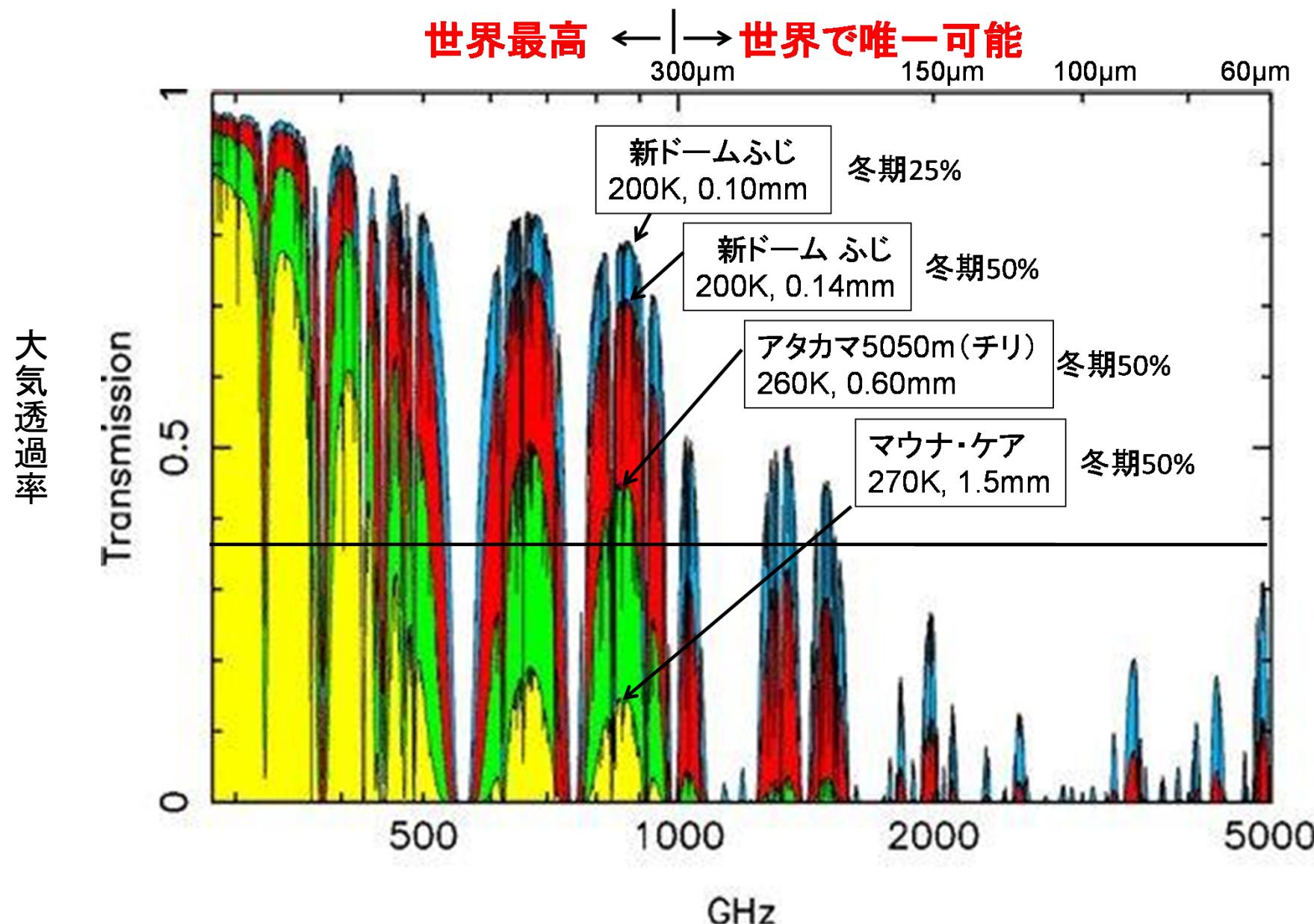
光学的厚み



ドームふじ基地で測定中の
ラジオメータ

夏季





大気の安定度

860 GHz = 350 μm @南極点

(Peterson etc 2003 PASP 115, 383)

大気の安定度：抜群に良い

(常に高気圧、夜は4ヶ月継続、雪面)

→特に連続波観測に有効

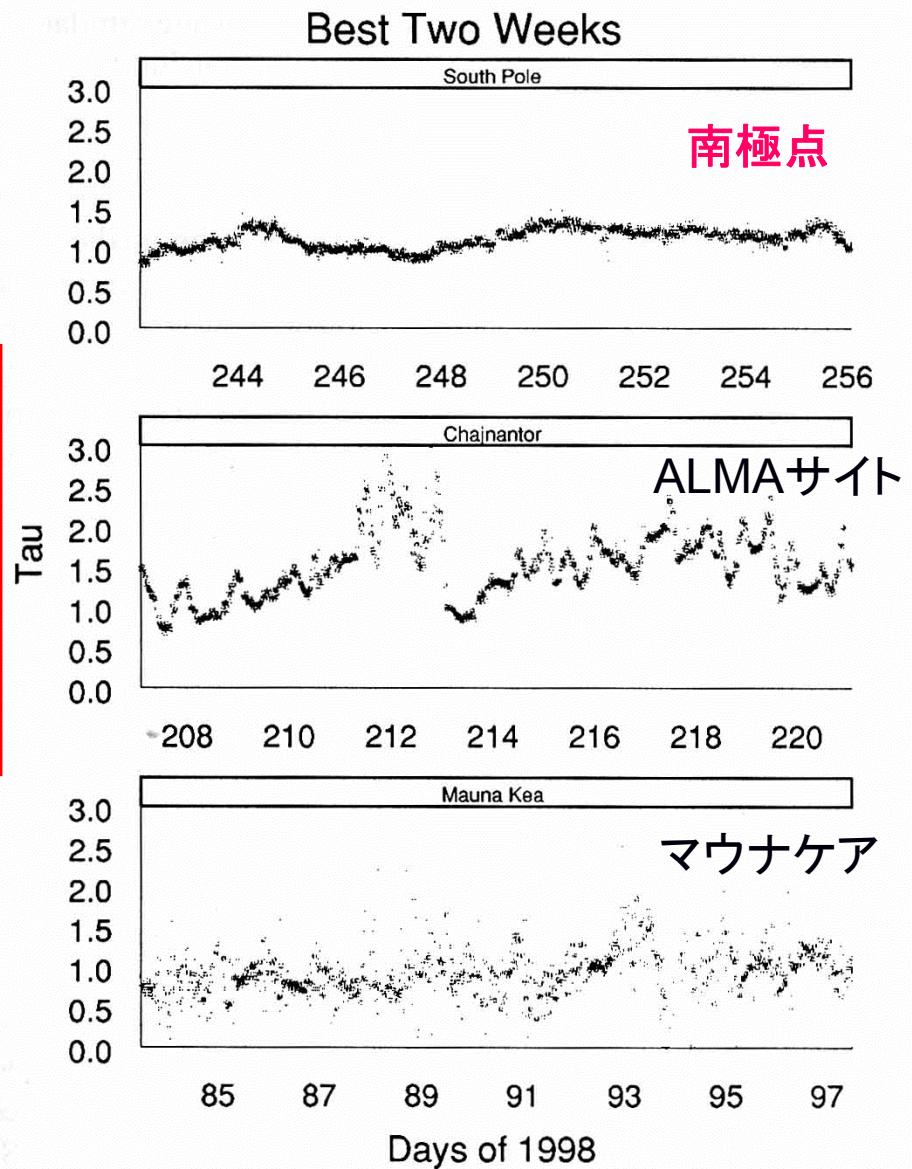
(ミリ波、サブミリ波でも)

干渉計

cf. チリ、マウナケア

「サブミリ波銀河」？

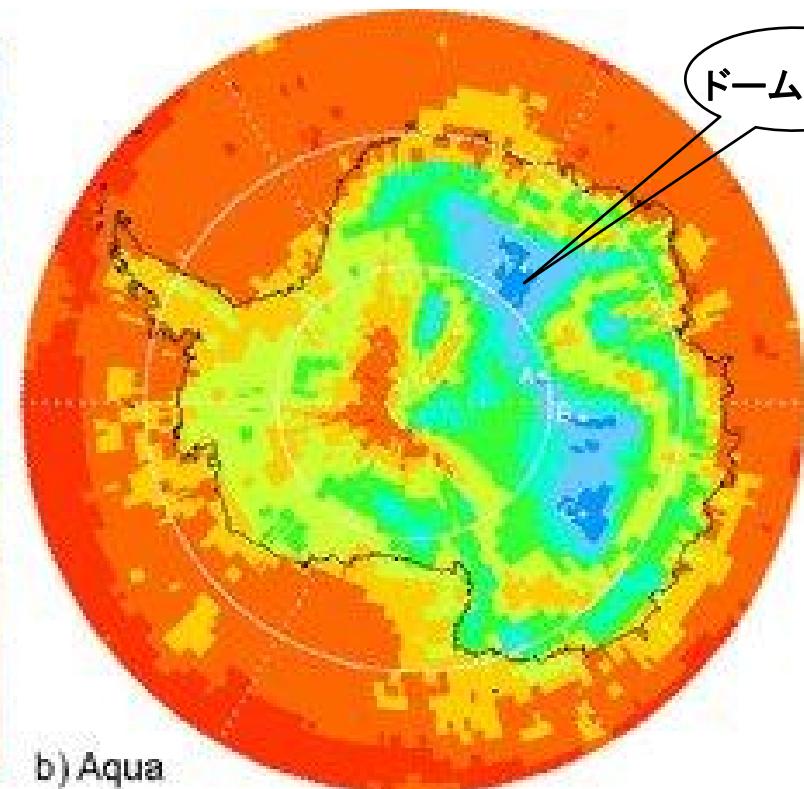
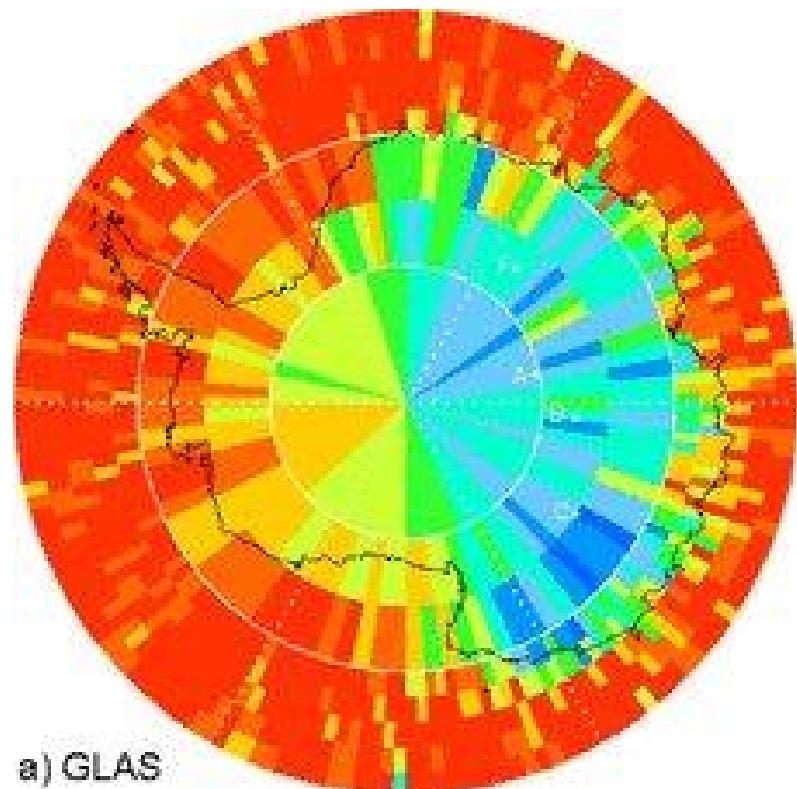
実態は0.8mm(350GHz)~2mm



晴天率

(W. Saunders, et al. 2009 PASP 121, 976)

夜間の雲量(年平均)一衛星観測



a) GLAS

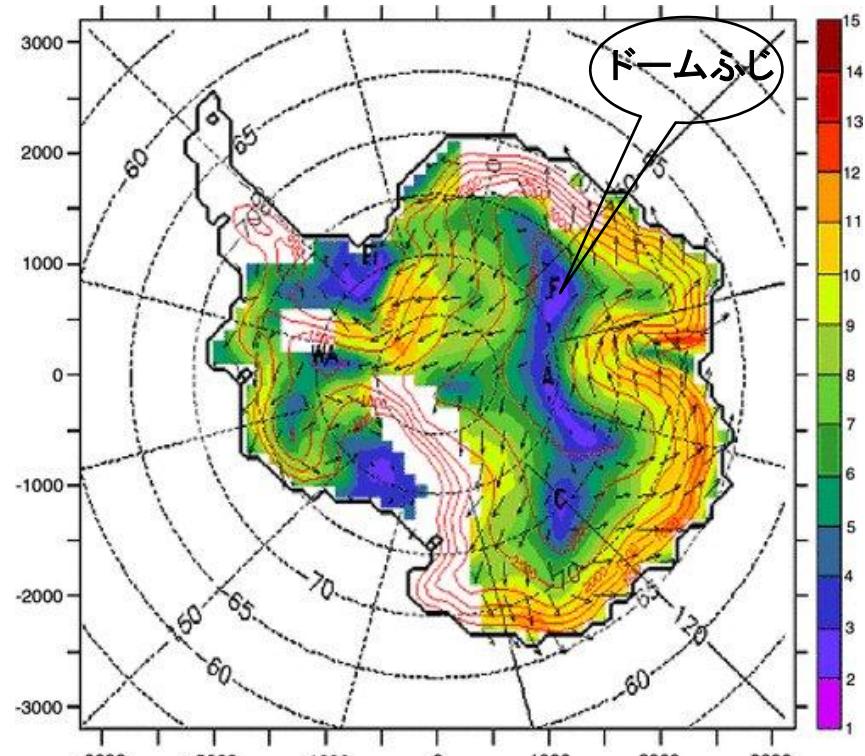
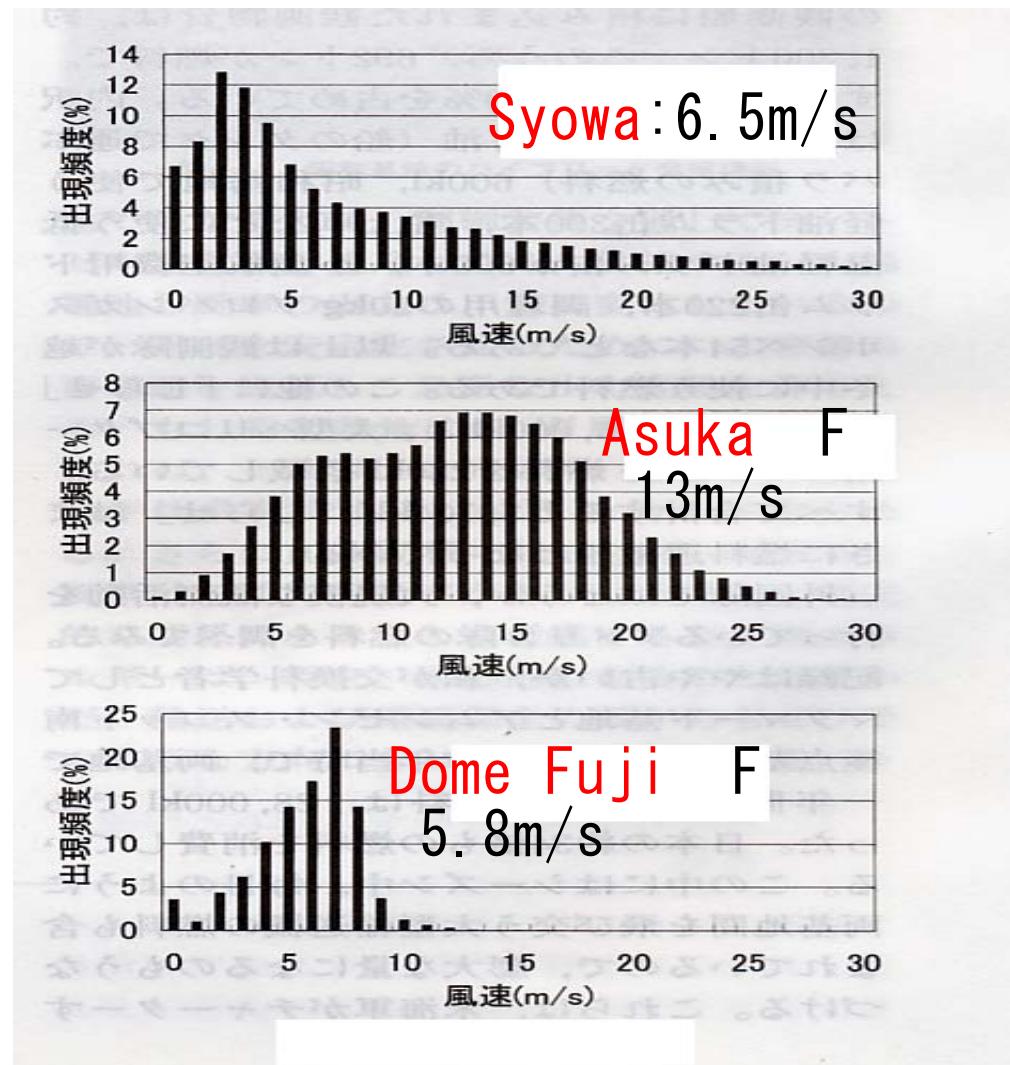
b) Aqua

ドームふじ
(極地研実測⇒)

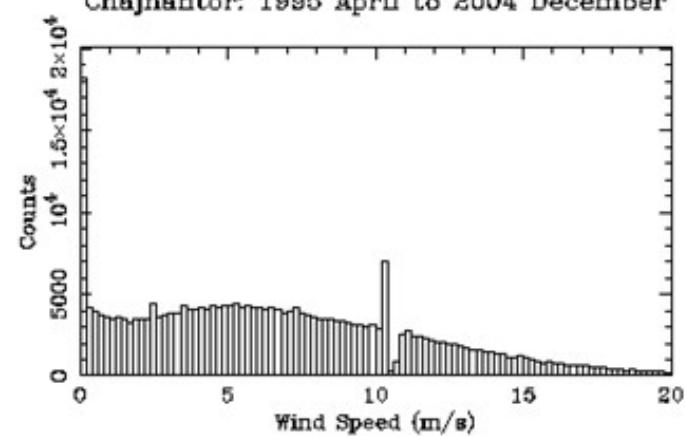
完全な晴天=68% (1994-95、年間)
晴天=8~9割?

風速

(→望遠鏡の指向性)

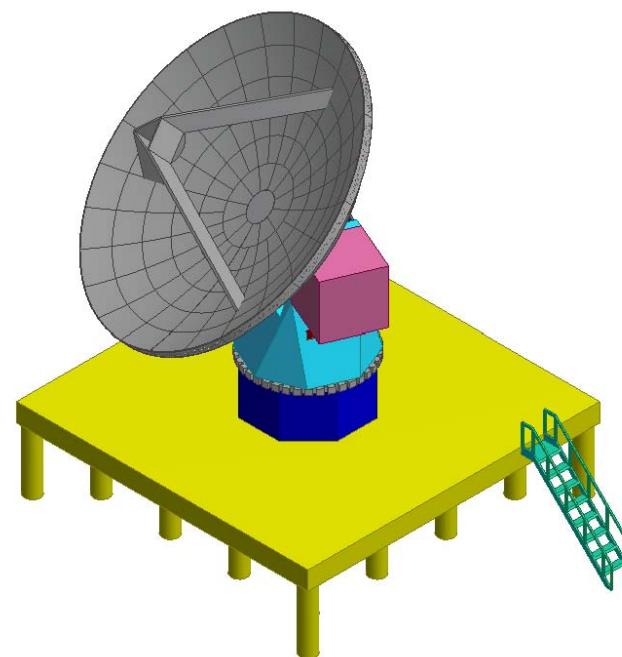
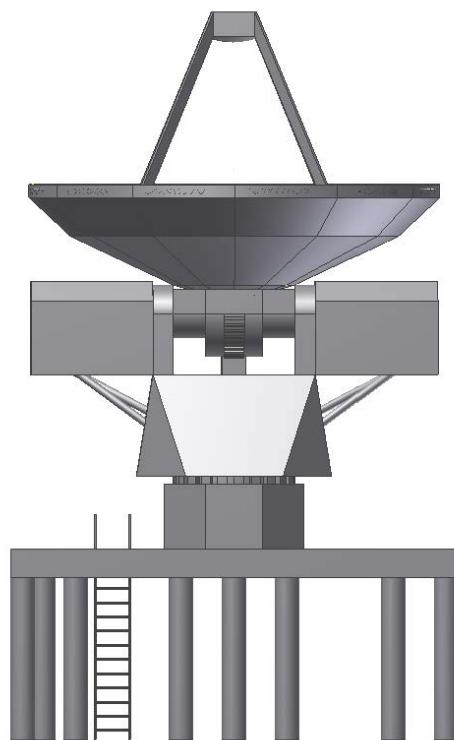


Surface Wind speed (m/s, JJA 2004)
Chajnantor: 1995 April to 2004 December



チリ: 5000m、平均6.1m

南極10mテラヘルツ望遠鏡

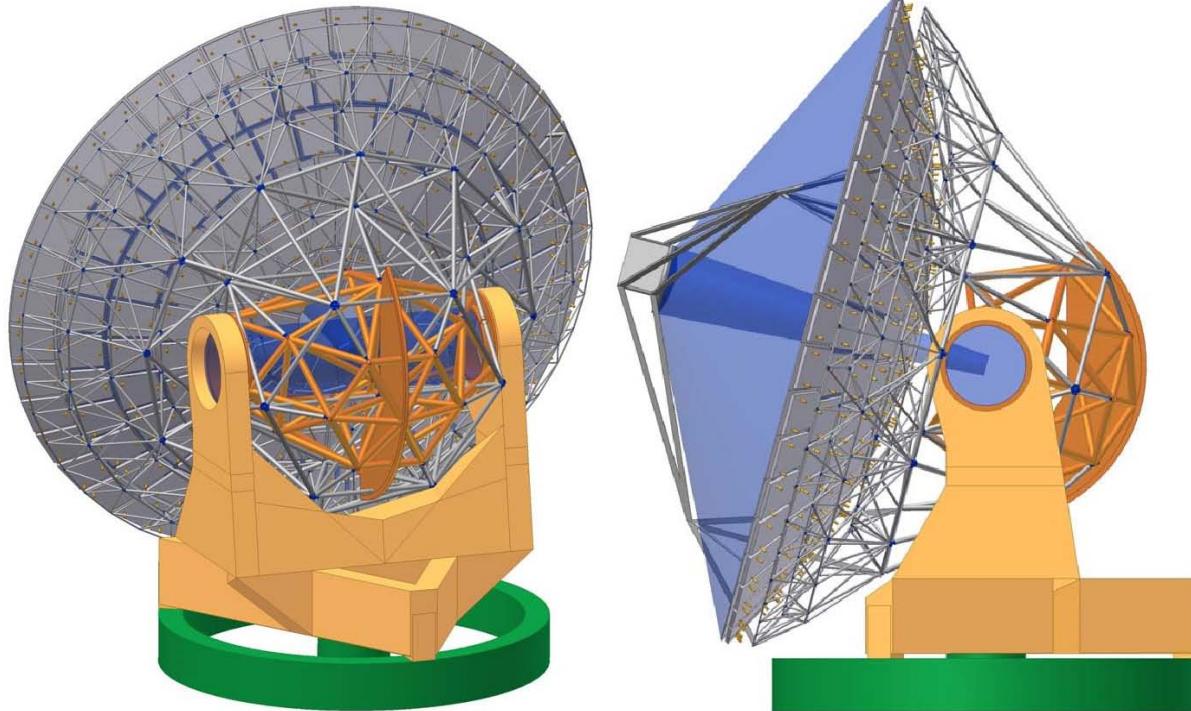


周波数

200GHz ~ 1.5 THz

@新ドームふじ基地

南極30mテラヘルツ望遠鏡計画



CCAT
D=25m
@チリ、アタカマ
コーネル大学ほか

Figure 1: Truss with a distributed CFRP (grey) to steel (orange) connection. Masses for this design are given in Table I and rod sizes are given in Table II.

⇒ 南極30m鏡 @新ドームふじ基地／南極

水素分子(H_2) / 電氣四重極子放射

TABLE 1
 H_2 PARAMETERS

$V=0$ Transition	Wavelength (μm)	Rotational State (J)	Energy ($E\ k^{-1}$)	A (s^{-1})	Statistical Weight (g)
$H_2(0-0) S(0)$	28.22	$2 \rightarrow 0$	510	2.94×10^{-11}	5
$H_2(0-0) S(1)$	17.04	$3 \rightarrow 1$	1015	4.76×10^{-10}	21
$H_2(0-0) S(2)$	12.28	$4 \rightarrow 2$	1682	2.76×10^{-9}	9
$H_2(0-0) S(3)$	9.66	$5 \rightarrow 3$	2504	9.84×10^{-9}	33
$H_2(0-0) S(4)$	8.03	$6 \rightarrow 4$	3474	2.64×10^{-8}	13
$H_2(0-0) S(5)$	6.91	$7 \rightarrow 5$	4586	5.88×10^{-8}	45

NOTE.—The statistical weight (g) is $(2J + 1)(2I + 1)$ where I equals 1 for odd J transitions (ortho transitions) and I equals 0 for even J transitions (para transitions).

(cf. CO $J=1-0$, $A=8 \times 10^{-8}$)

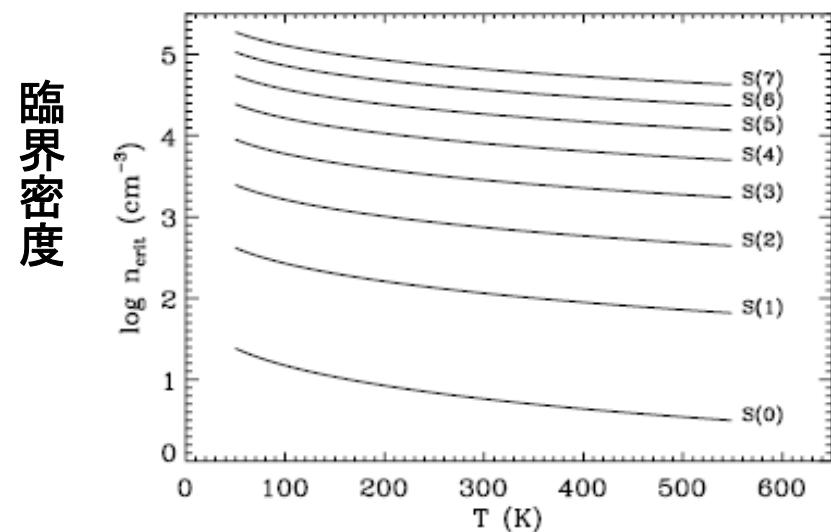
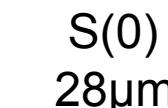
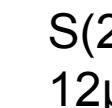
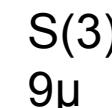
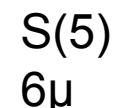
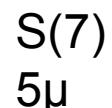
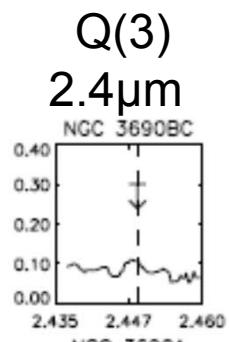


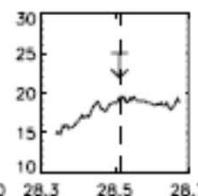
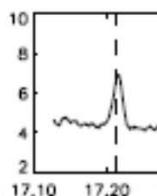
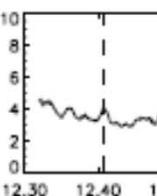
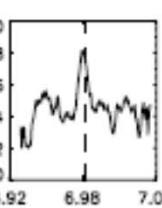
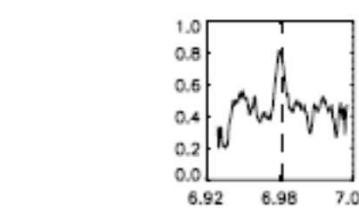
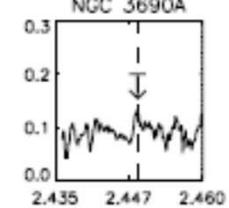
FIG. 3.—Critical densities for collisional de-excitation by H_2 for the rotational transitions in the wavelength range of the IRS instrument.

銀河での観測例

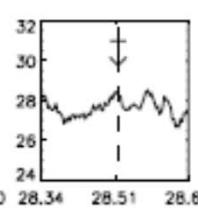
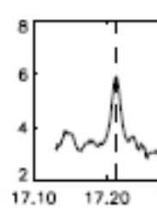
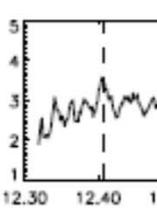
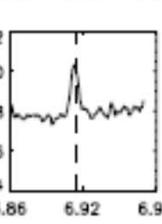
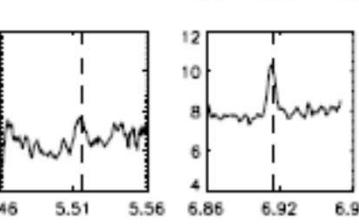
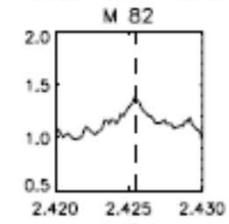
N3690B



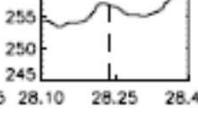
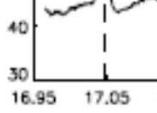
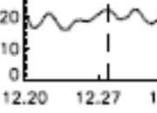
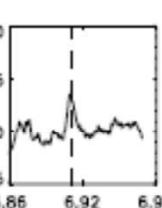
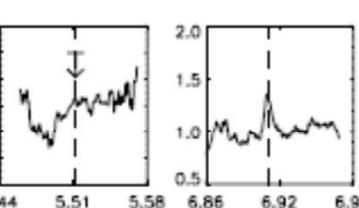
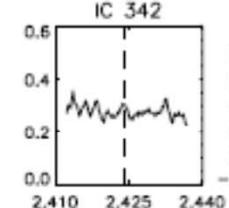
N3690A



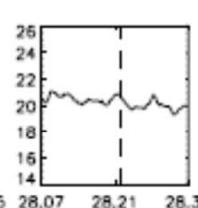
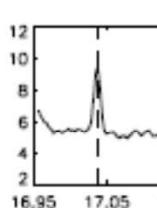
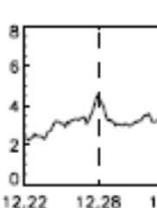
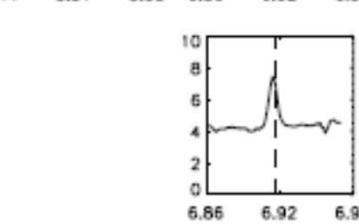
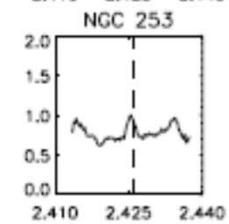
M82



IC342



N253



ISO (D.Rigopoulou, et al. 2002 A&A 389, 374)

Fig. 1. H₂ molecular lines from starbursts: from left to right (1-0)Q(3), (0-0)S(7), (0-0)S(5), (0-0)S(3), (0-0)S(2), (0-0)S(1)

LTE

ボルツマン分布

$$\frac{N_u}{N_{tot}} = \frac{g_u}{Z(T_{ex})} \exp\left(-\frac{E_u}{kT_{ex}}\right)$$

$$\log(N_u/g_u) = \log(N_{tot}/Z(T_{ex})) - \frac{1}{T_{ex}} \frac{E_u}{k}$$

励起温度 Tex

Spitzer

S.J.U. Higdon, et al.
2006 ApJ 648, 323

Assuming
ortho/para = 3
(>200 K)

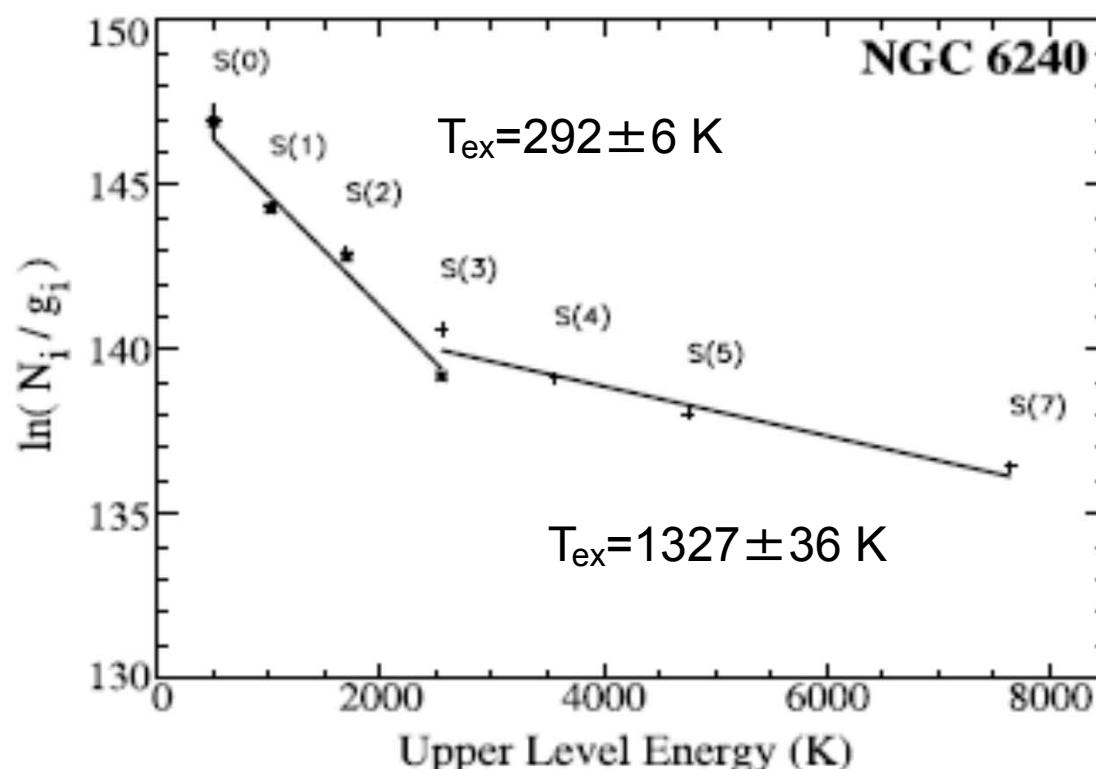


Fig. 8.—Molecular hydrogen excitation diagram for NGC 6240. The $S(3)$ – $S(7)$ values can be fit by a hot ($T_{ex} = 1327 \pm 36$ K) H_2 component. A second cooler ($T_{ex} = 292 \pm 6$ K) gas component is found after subtracting this component from the $S(0)$ – $S(3)$ values (replotted as asterisks) prior to modeling.

H_2 in M51 (Spitzer: G.Brunner, et al. 2008 ApJ 675, 316)

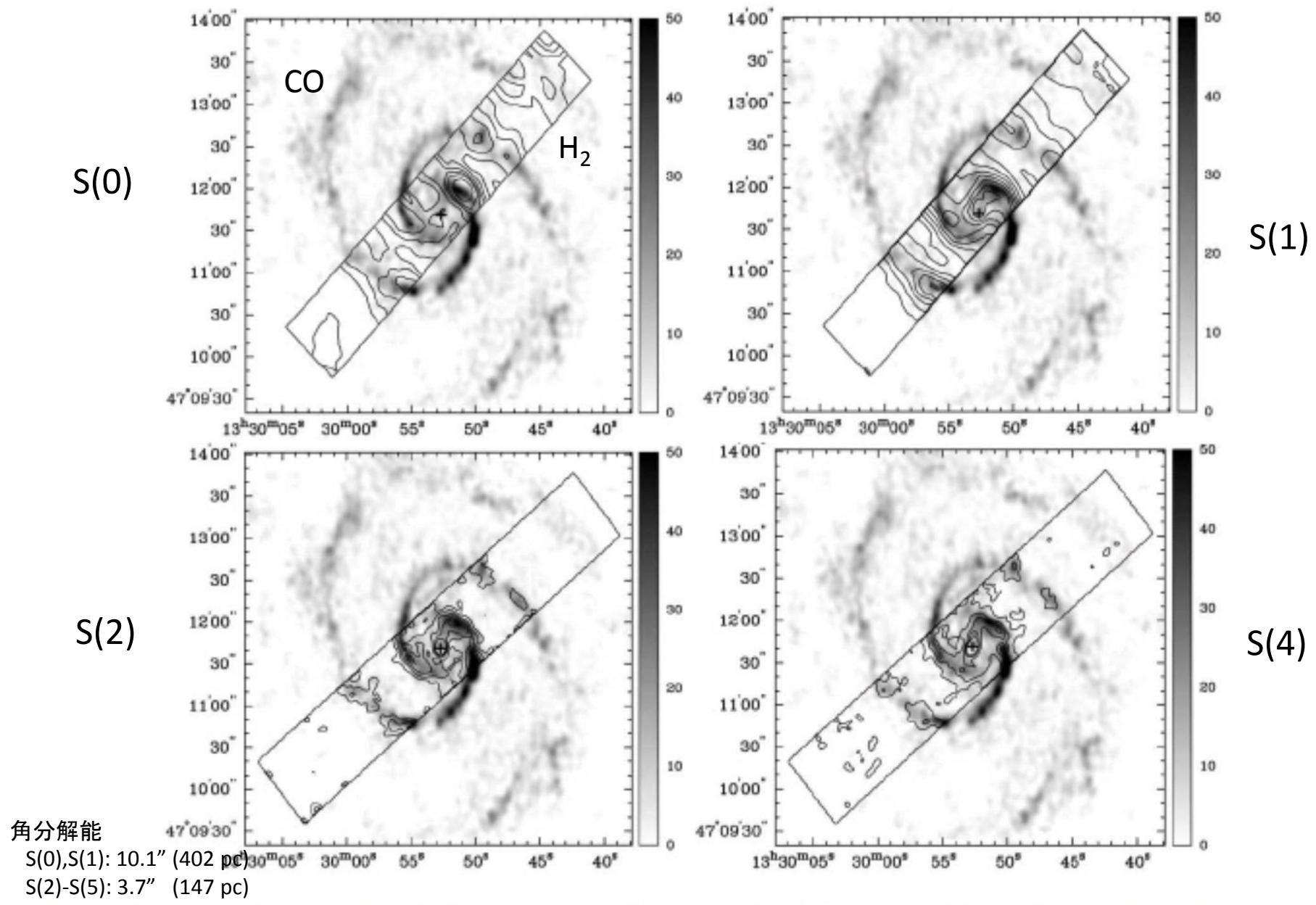
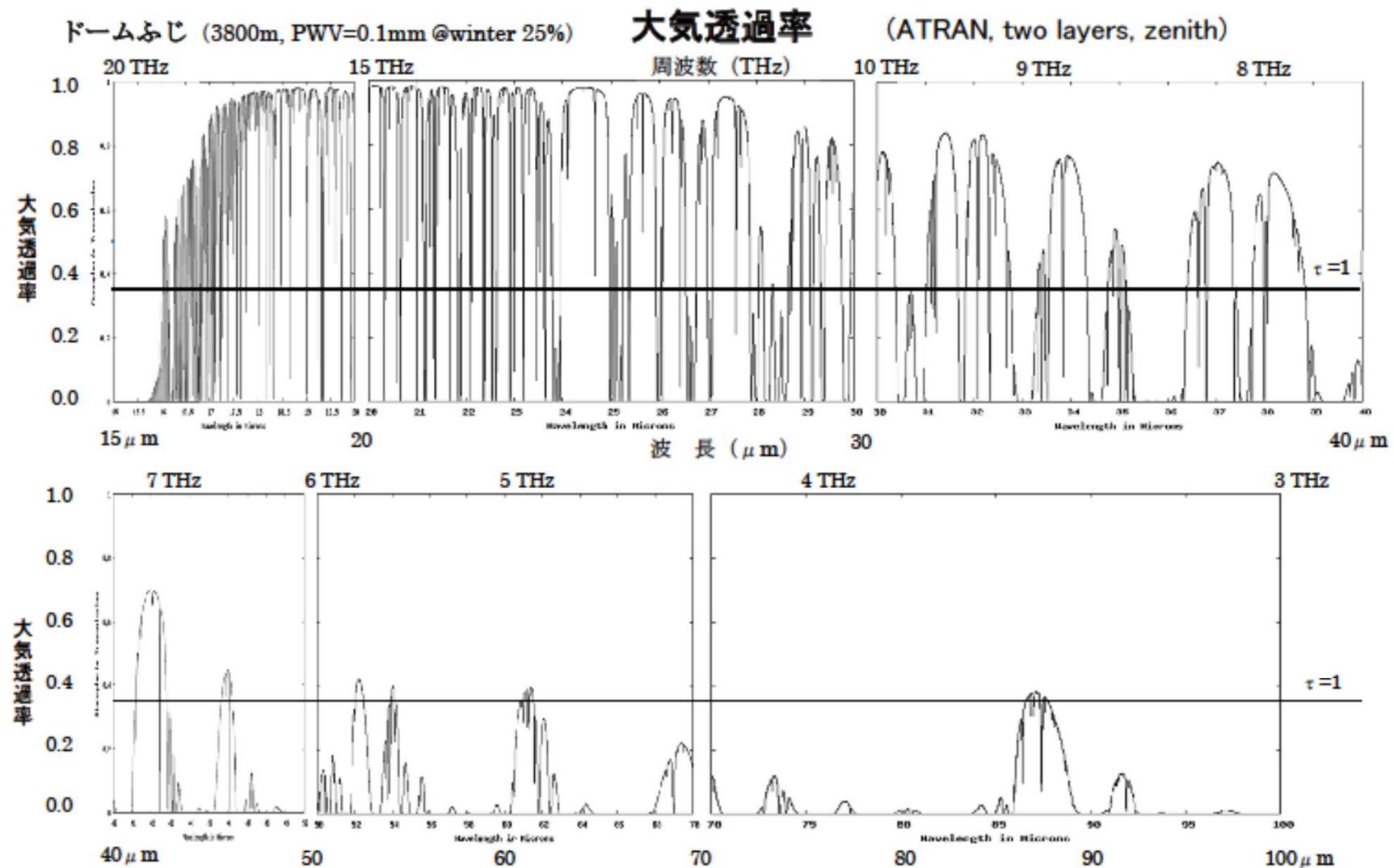
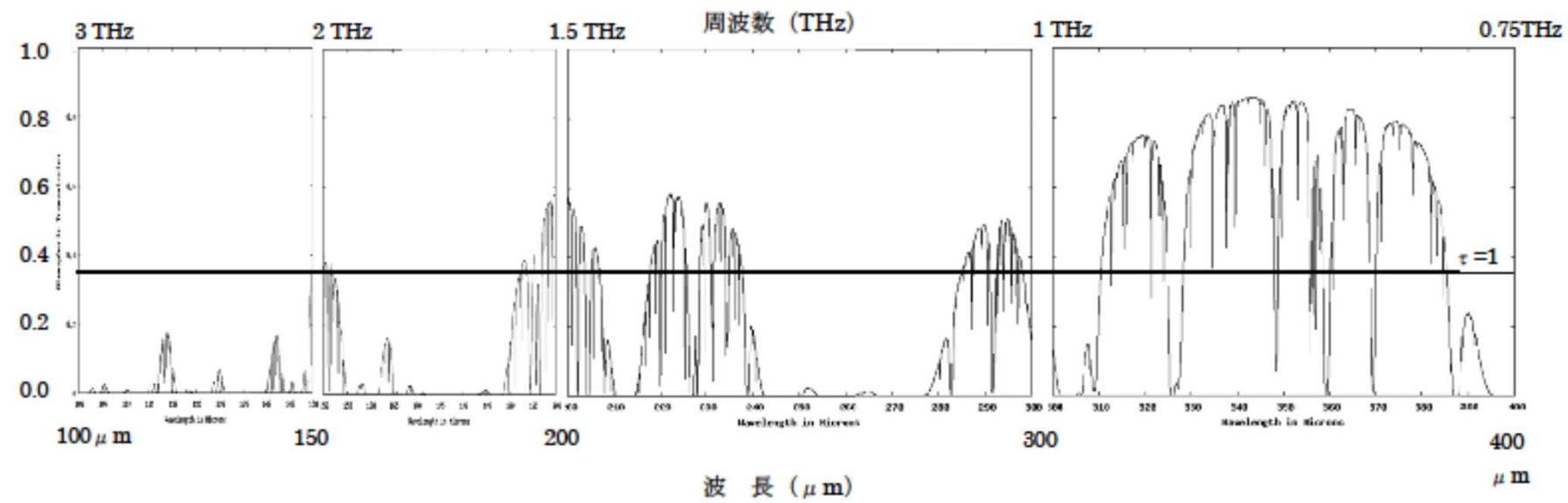
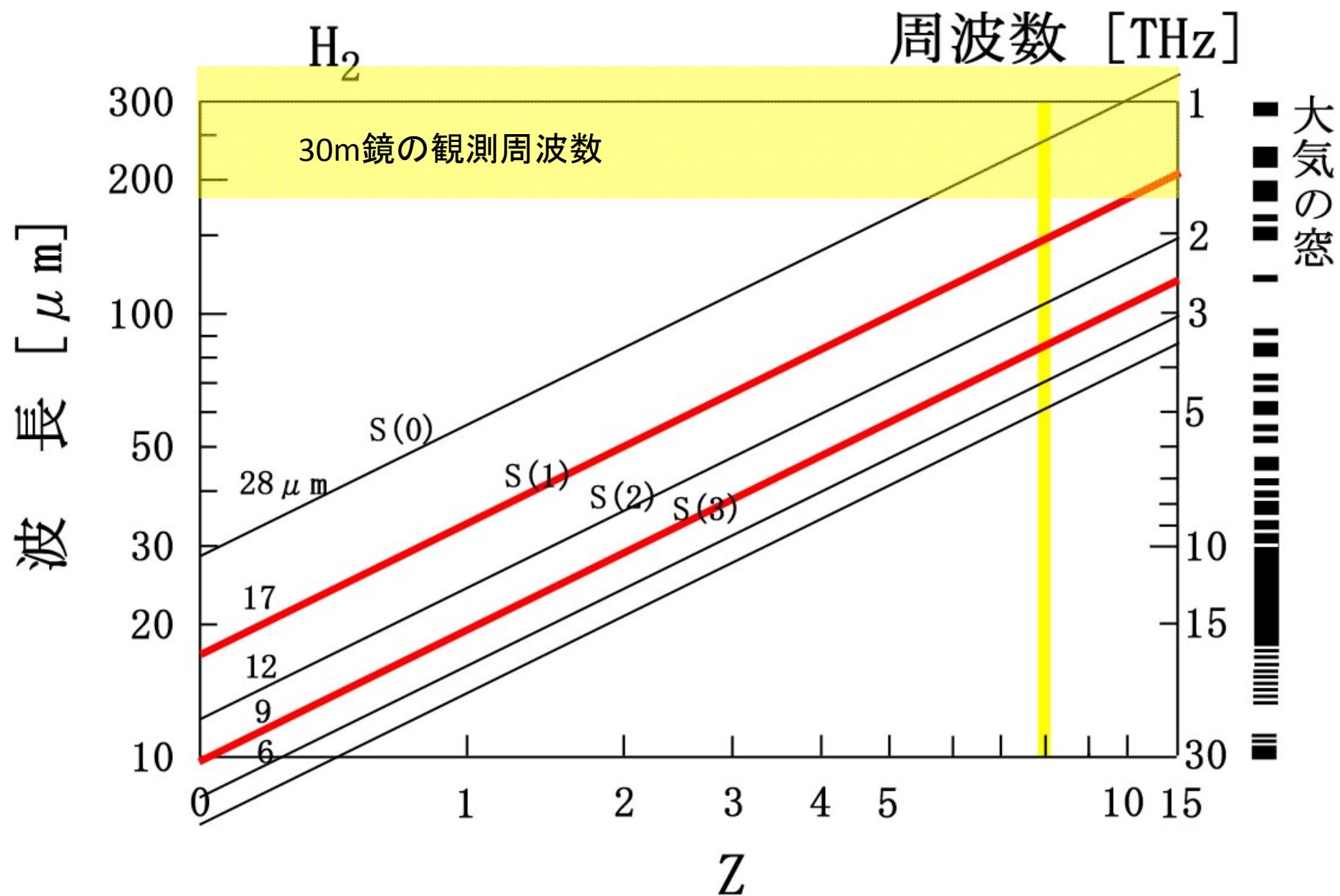


Fig. 10.—Comparison of the CO emission to the H_2 S(0) (top left), H_2 S(1) (top right), H_2 S(2) (bottom left), and H_2 S(3) (bottom right) emission. The CO emission maps are in units of Jy km s^{-1} . Contour levels for H_2 S(0), H_2 S(1), H_2 S(2), and H_2 S(3) are the same as in Fig. 3.

H_2 は観測可能か？：周波数







H_2 は観測可能か？：感度

南極30m鏡

+電波カメラ(MKID)：低分散分光($R \sim 1000$)
ピクセル～100－3000

$T_{RX} \sim 1\text{ K}$

$\Delta V \sim 300\text{ km/s} \sim 1\text{ GHz}$ for H_2



周波数	感 度 (5rms)	
	積分時間＝1時間	積分時間＝10時間
850 GHz	2.3 mJy	0.7 mJy
1.0 THz	10	3.3
1.3 THz	12	3.8
1.5 THz	16	5.0

期待される強度

初代星形成 (Mizusawa,etc 2004 PASJ 56,487)

1+z=20 (15?)

$F_{\text{peak}} \sim 10^{-29} \text{ W/m}^2$ for $M = 10^2 M_0$

$S_{\text{peak}} \sim 10^{-5} \mu\text{Jy}$ for $v_0 V/c \sim 10^{10} \text{ Hz}$ X

銀河形成 (Omukai,Kitayama 2003 ApJ 599,738)

$z=8$, (Dwarf gal → Giant gal)

$F_{\text{peak}} \sim 10^{-22} \text{ W/m}^2$ [S(1)] for $M = 10^9 M_0$

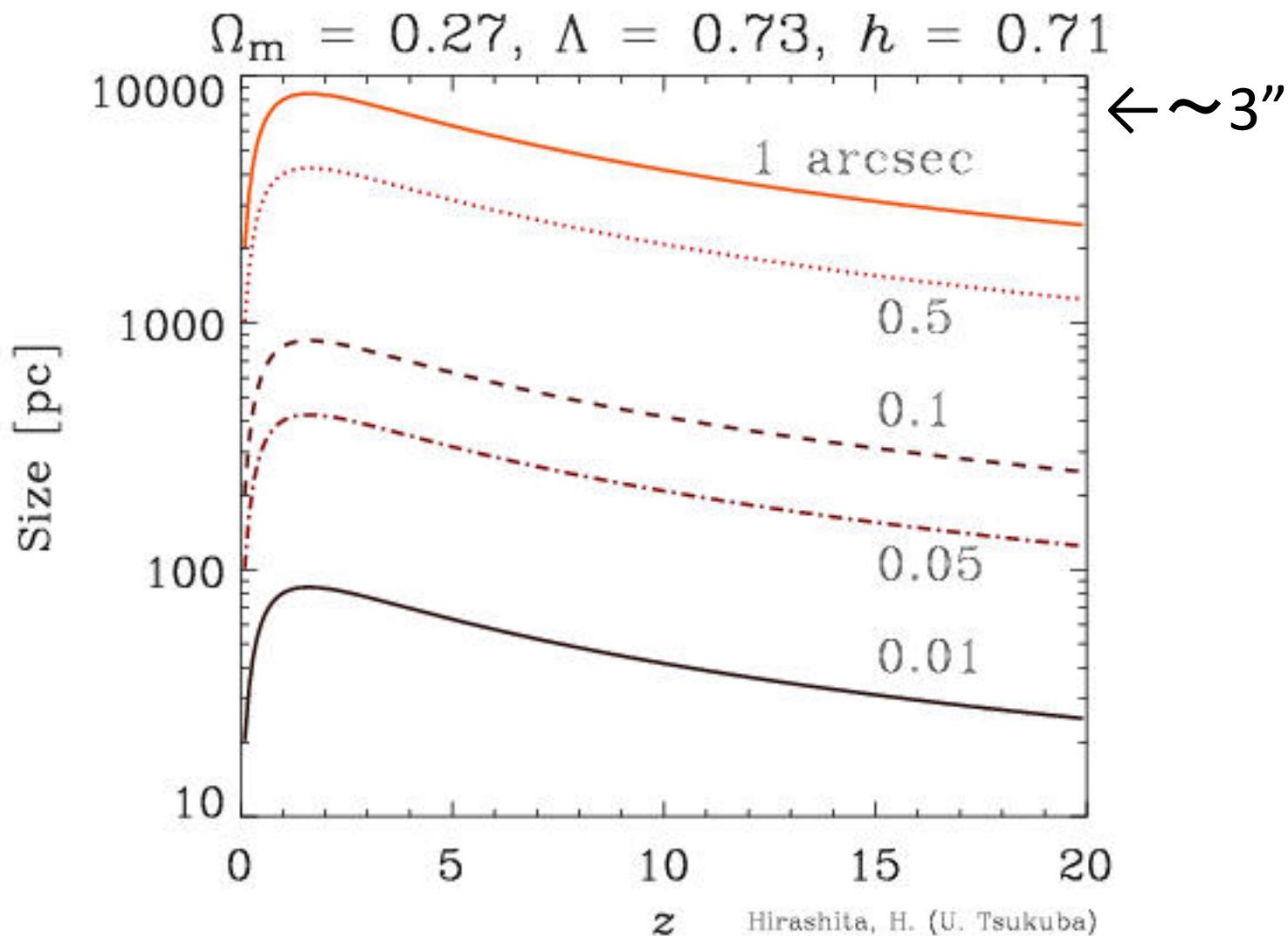
$S_{\text{peak}} \sim 0.01 \text{ mJy}$ X

$F_{\text{peak}} \sim 10^{-20} \text{ W/m}^2$ [S(1)] for $M = 10^{11} M_0$

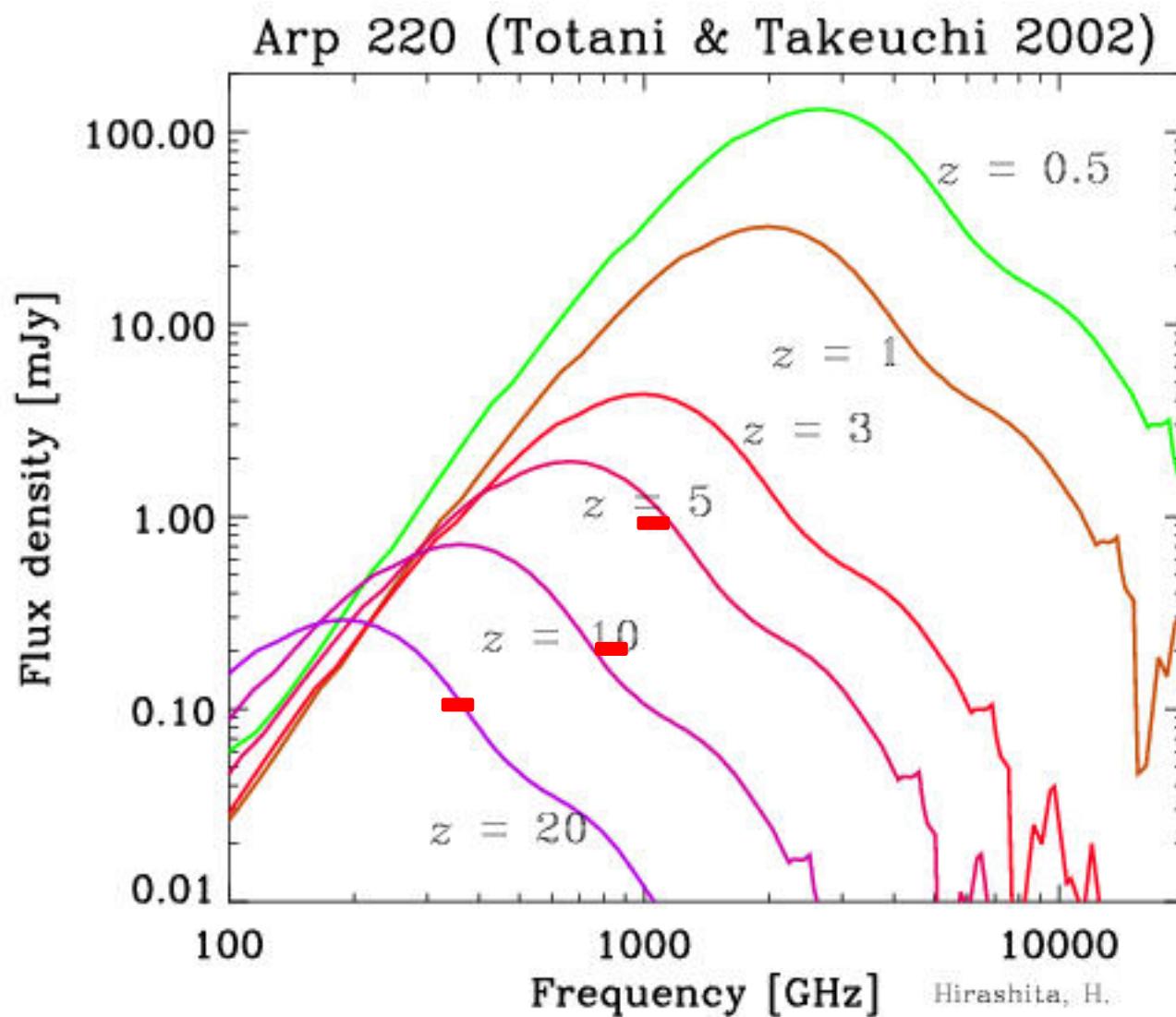
$S_{\text{peak}} \sim 1 \text{ mJy}$ なんとか可能かも

(重力レンズに期待?)

角分解能



参考:ダストの観測



まとめ

南極30mテラヘルツ望遠鏡

宇宙初期の水素分子は検出できるか？

○周波数(<1.5 THz)

H_2 S(0) @ $z>=5.5$

S(1) @ $z>= 10$

○感度(5rms～mJy)

個々の星形成領域($M \sim 10^2 M_\odot$)は不可

$M \sim 10^{11} M_\odot$ の塊は、なんとか可能そう

(とにかくやってみる 例:CO)

衛星搭載赤外線望遠鏡(D~3m)

○感度は～1桁高い (角分解能は1桁悪い)