彗星起源の$CO+CO_2$および‌ケイ酸塩ダストの近中間赤外線分光観測

大坪 貴文（ISAS/JAXA）

「ALMAワークショップ：円盤から太陽系へ」
2018年11月21日-22日 ＠WTC Conference Center Tokyo

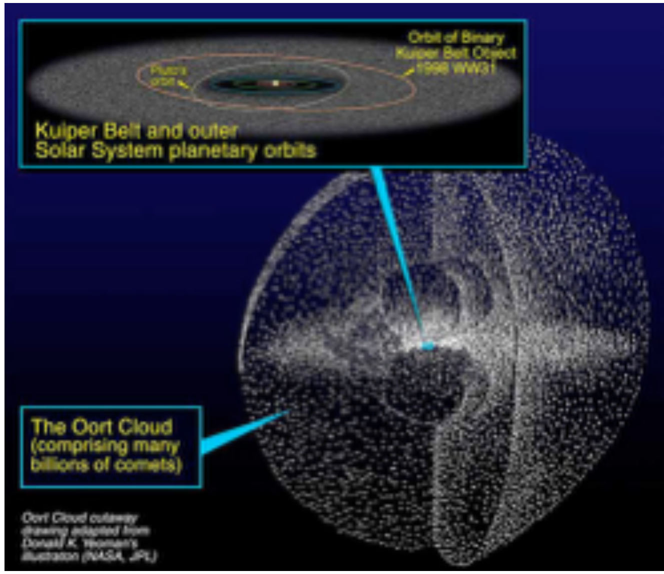
Comets

Comets

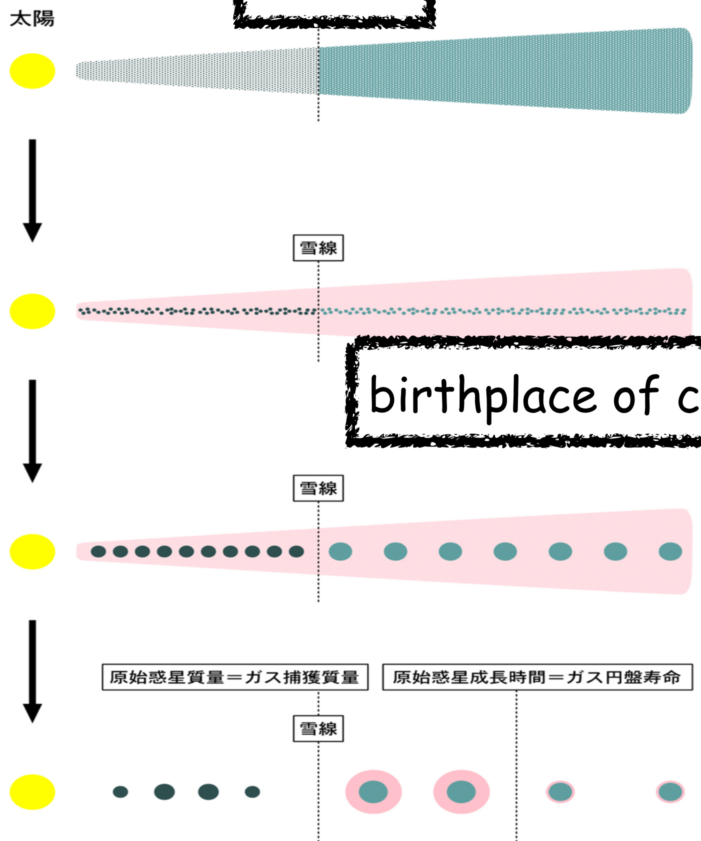
- primordial icy materials and refractory dust grains

cometary ices

- the oxidation environment in the early solar nebula
- link with interstellar ices

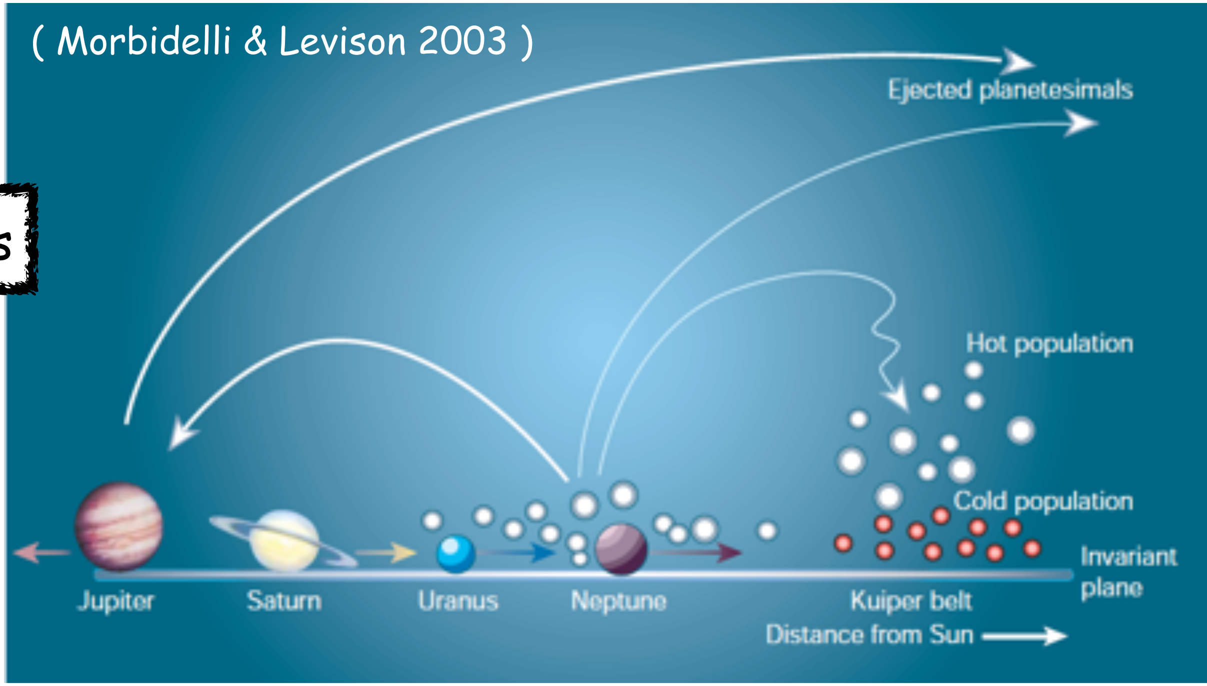


Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustration (NASA, JPL)



snow line

birthplace of comets



(Morbidelli & Levison 2003)

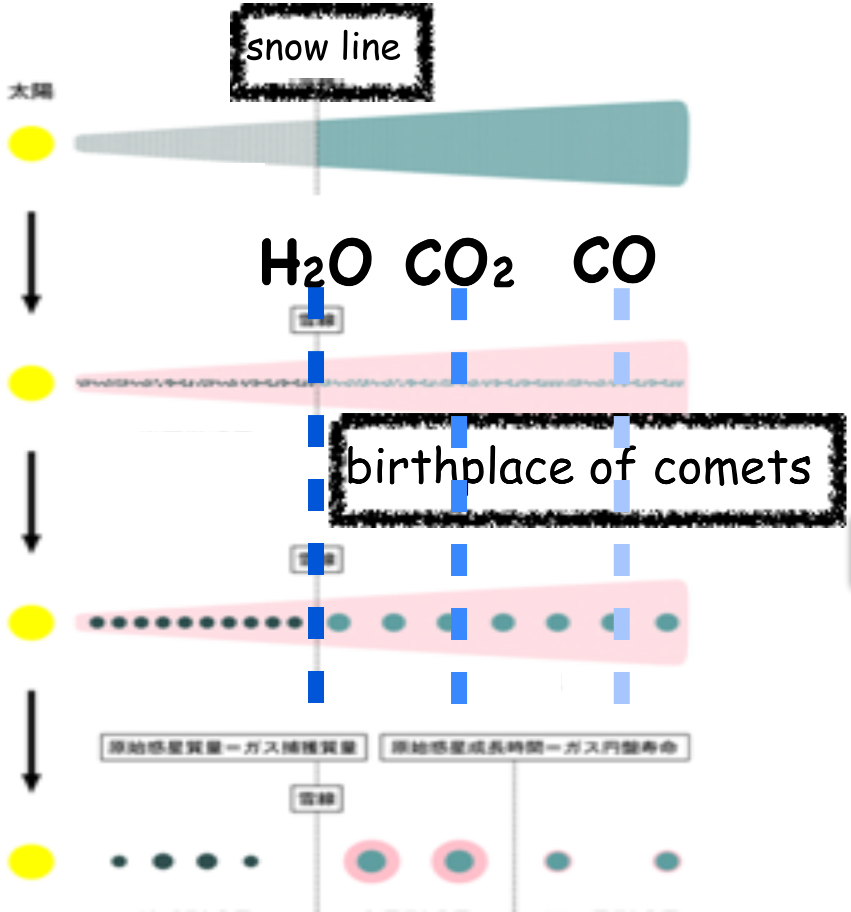
Cometary ices

Comets

- primordial icy materials and refractory dust grains

cometary ices (H_2O, CO_2, CO…)

- the oxidation environment in the early solar nebula
- link with interstellar ices



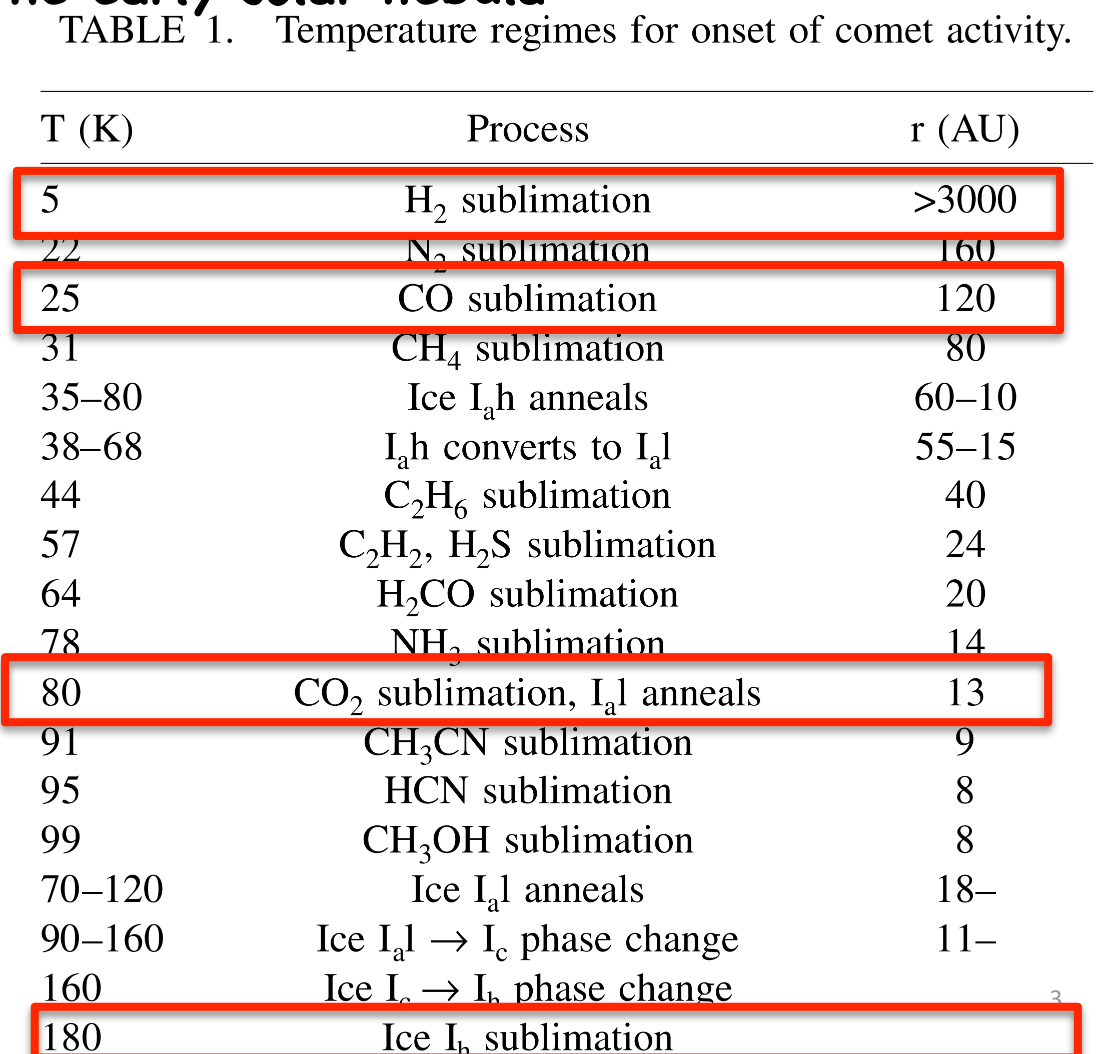
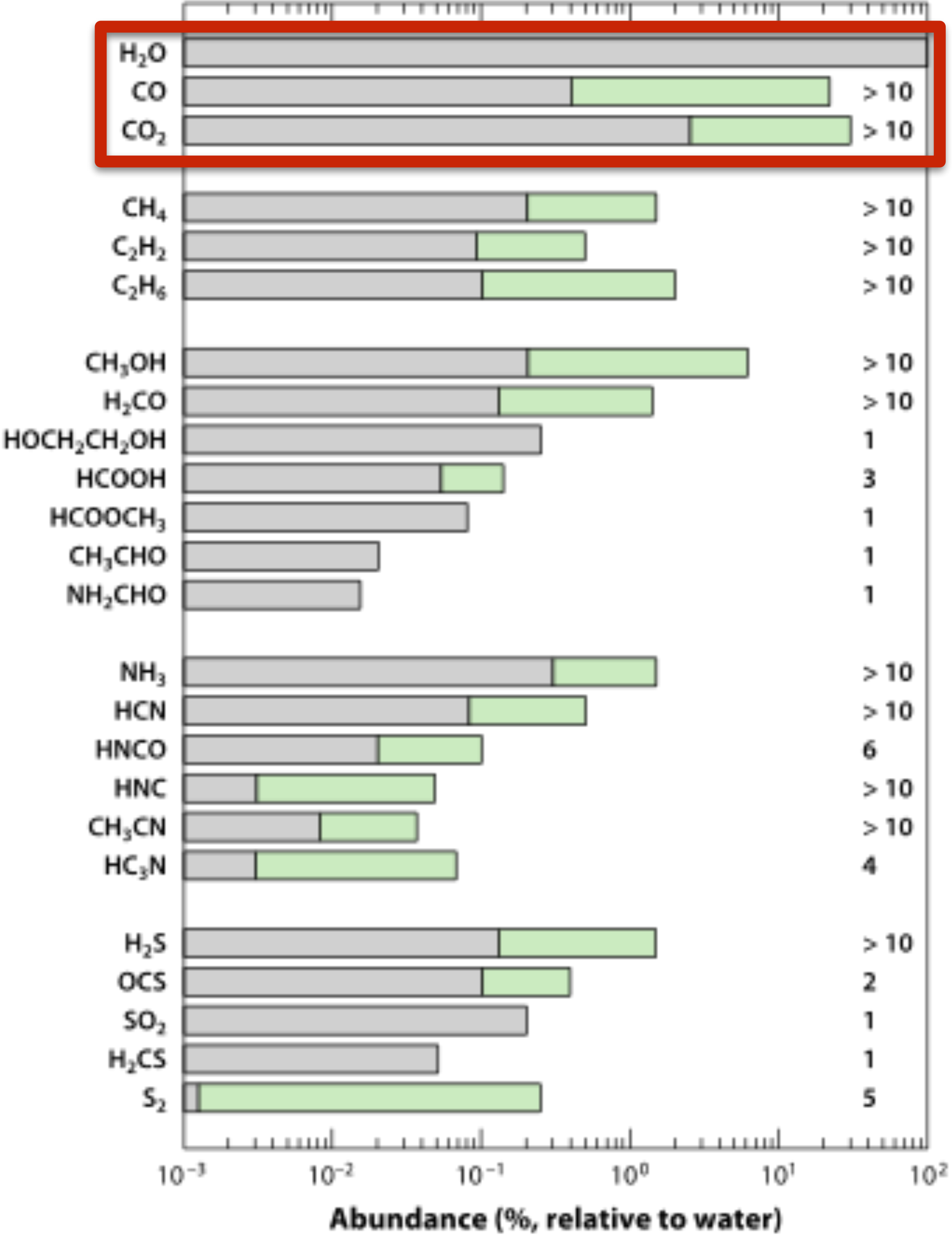


TABLE 1. Temperature regimes for onset of comet activity.

T (K)	Process	r (AU)
5	H_2 sublimation	>3000
22	N_2 sublimation	160
25	CO sublimation	120
31	CH_4 sublimation	80
35–80	Ice I_ah anneals	60–10
38–68	I_ah converts to I_al	55–15
44	C_2H_6 sublimation	40
57	C_2H_2, H_2S sublimation	24
64	H_2CO sublimation	20
78	NH_3 sublimation	14
80	CO_2 sublimation, I_al anneals	13
91	CH_3CN sublimation	9
95	HCN sublimation	8
99	CH_3OH sublimation	8
70–120	Ice I_al anneals	18–
90–160	Ice I_al → I_c phase change	11–
160	Ice I_c → I_h phase change	
180	Ice I_h sublimation	

Chemical composition of comets



Cometary CO$_2$ and CO

✳ The most abundant species in cometary ices after H$_2$O.

✳ While CO can be accessed in radio and near-IR domains from the ground-based observatories,

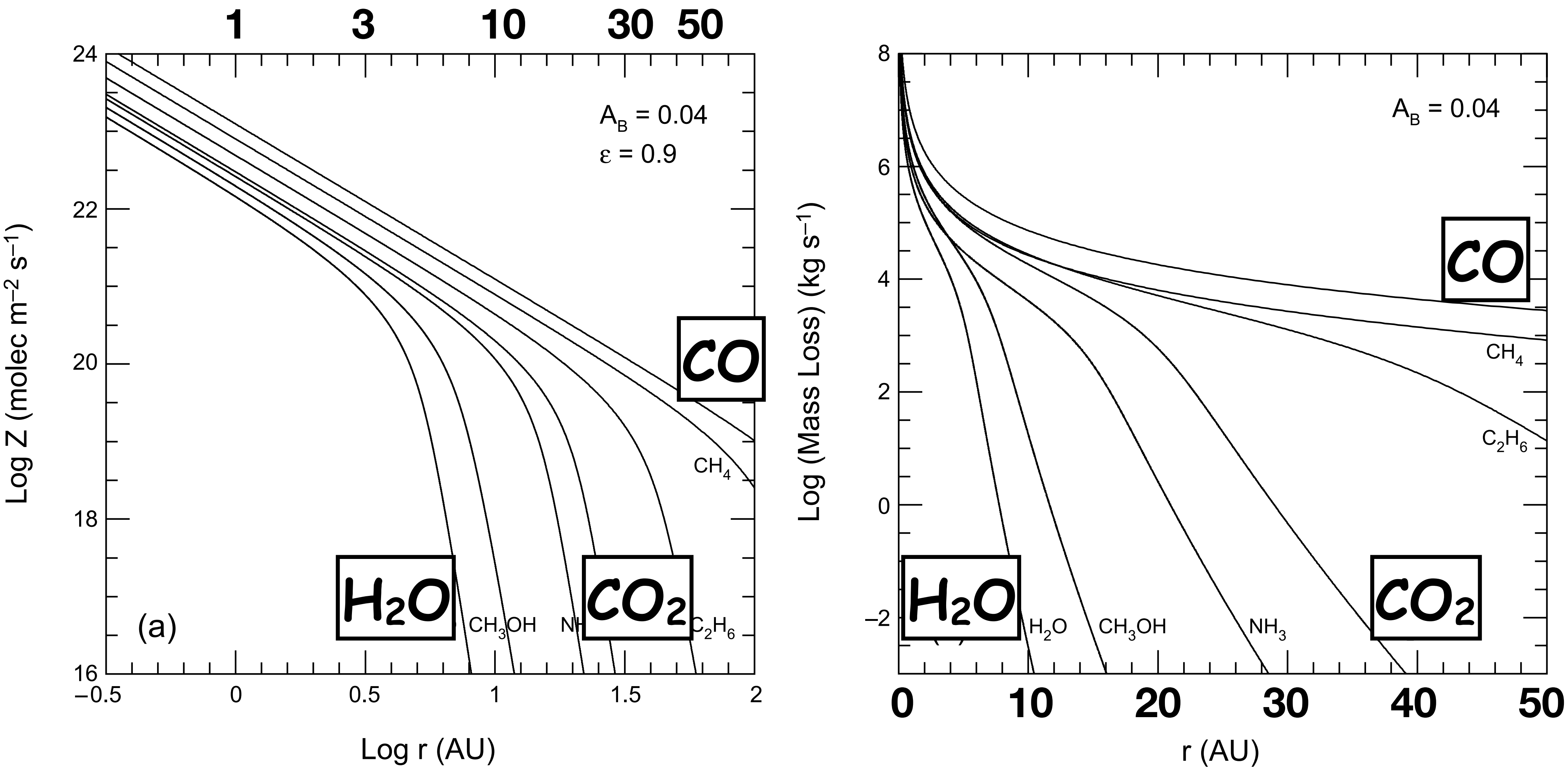
CO$_2$ cannot be observed due to the severe absorption by the telluric atmosphere.

✳ To detect cometary CO$_2$ directly,

observations from space are needed !!

(Mumma+Charnley, ARAA, 2011)

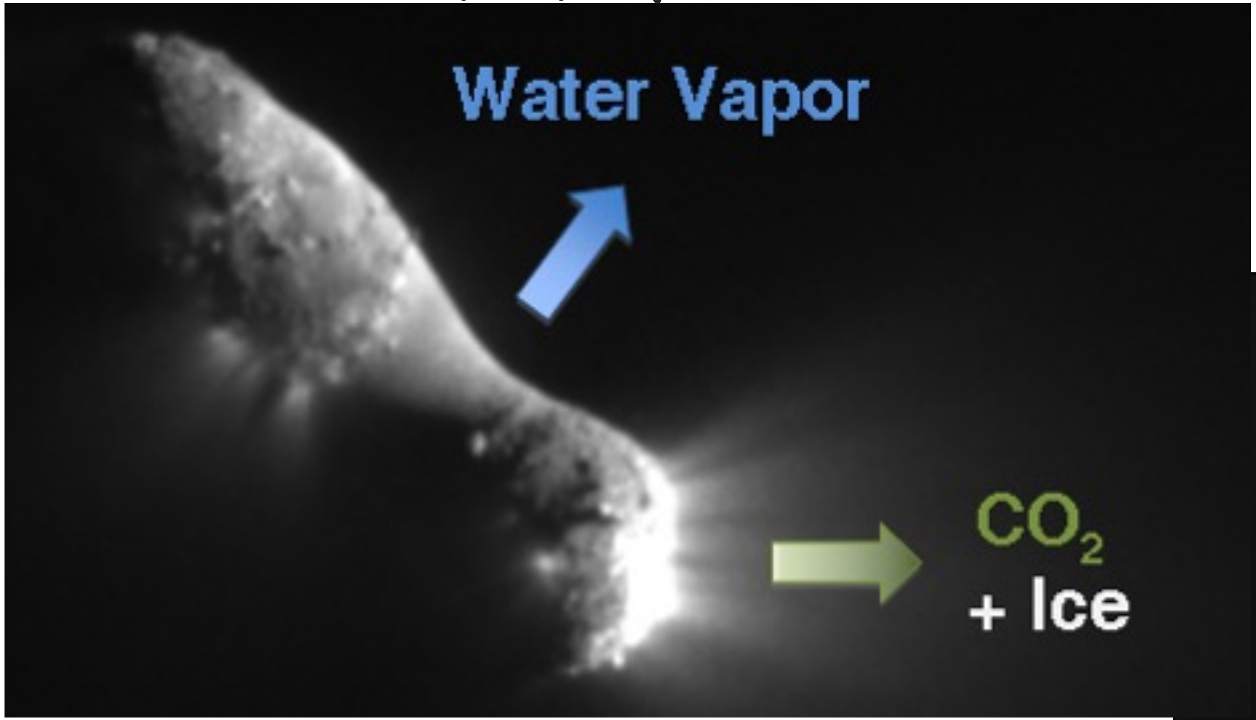
Driving force of comet activity



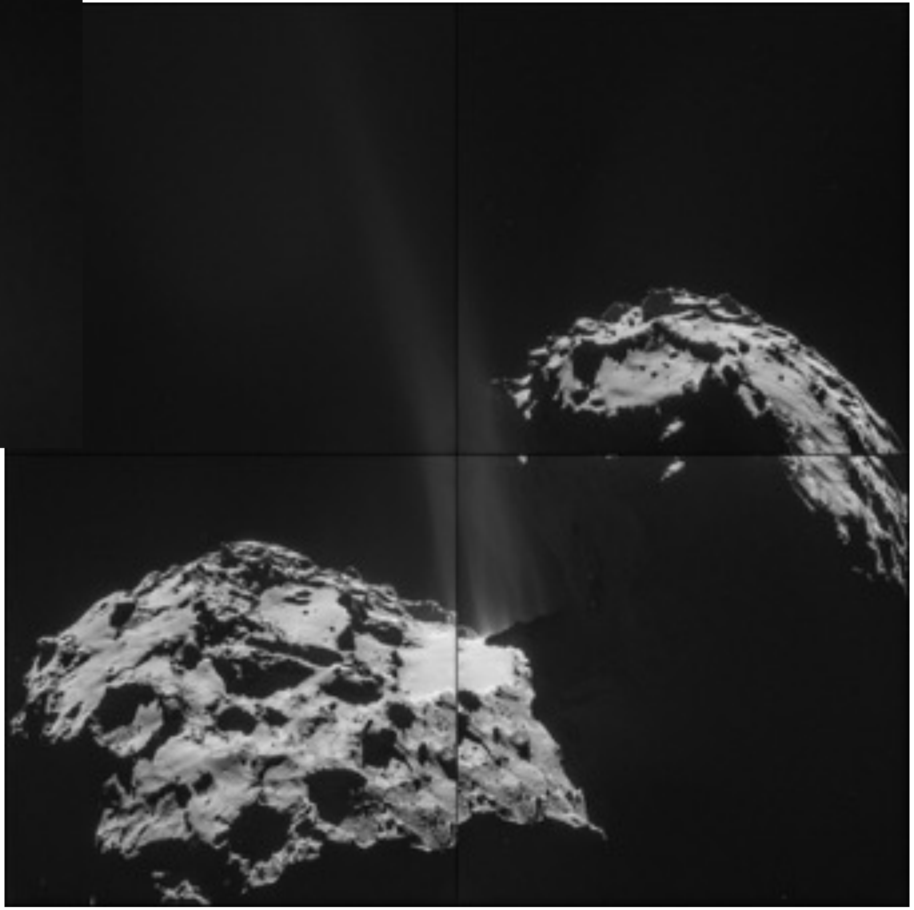
(Meech+ 2004, Comets II)

Driving force of comet activity

103P/Hartley by Epoxi (NASA)



CO_2 is the main driving force of comet activities!!



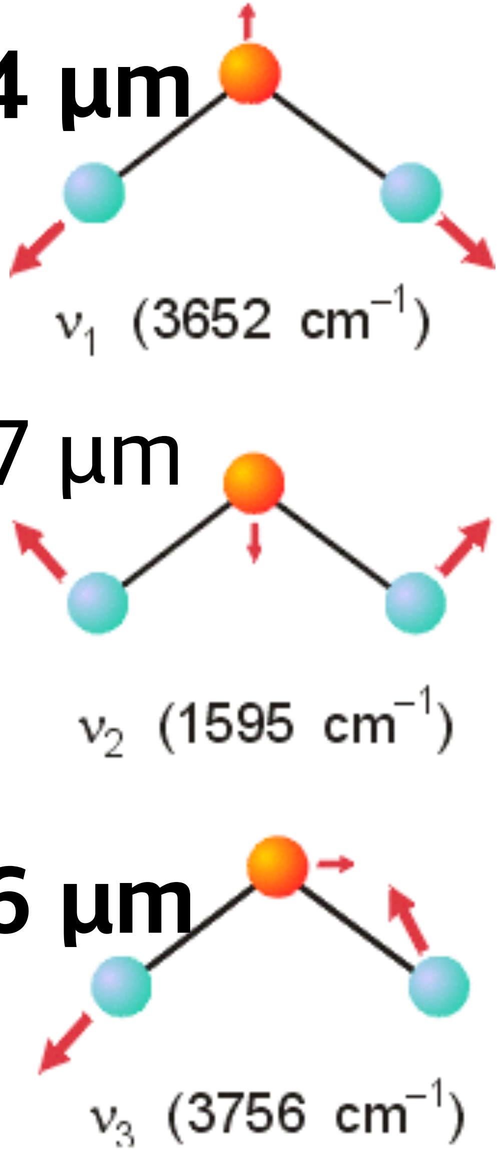
67P/CG by Rosetta (ESA)

AKARI Near-IR Spectroscopic Survey for CO_2 in Comets

Ootsubo+ 2012, ApJ, 752, 15
Ootsubo+ 2010, ApJL, 717, 66

T. Ootsubo, H. Kawakita,
S. Hamada, H. Kobayashi, M. Yamaguchi,
F. Usui, et al.

分子の振動モード（近赤外線）

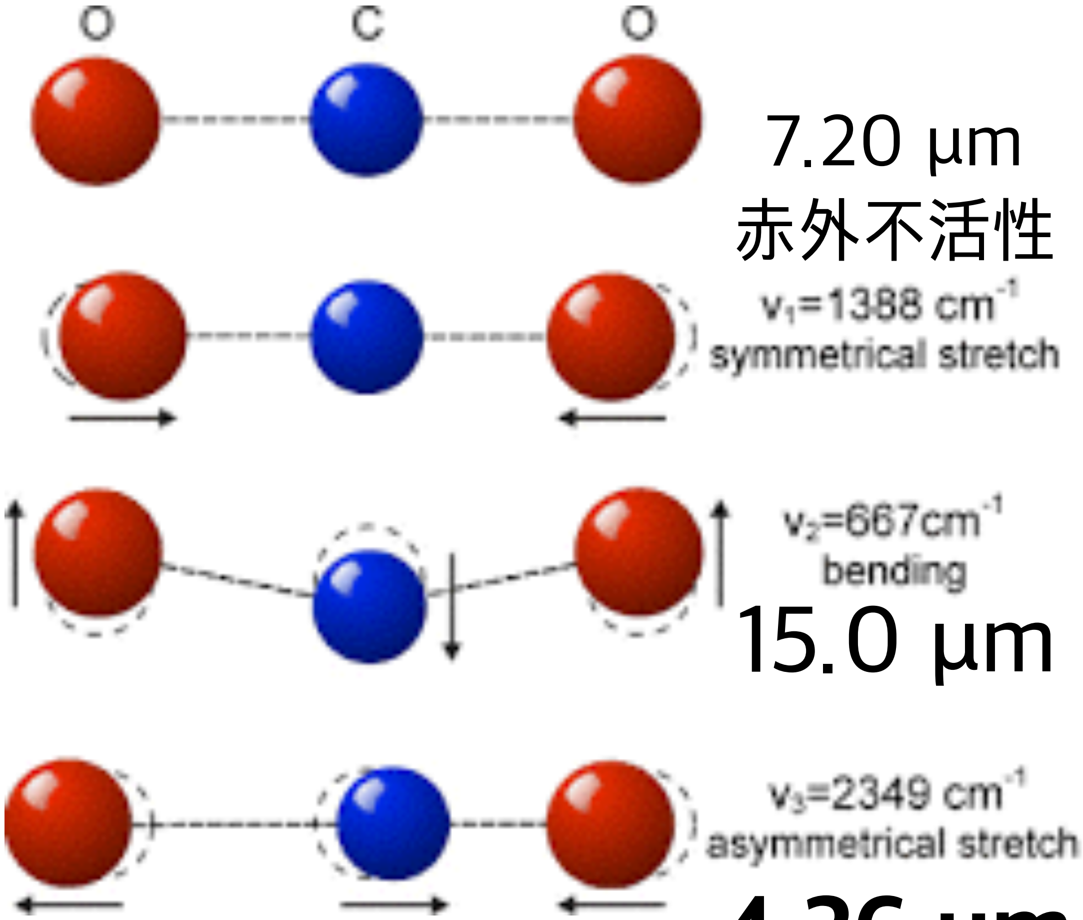


2.74 μm

6.27 μm

2.66 μm

H_2O



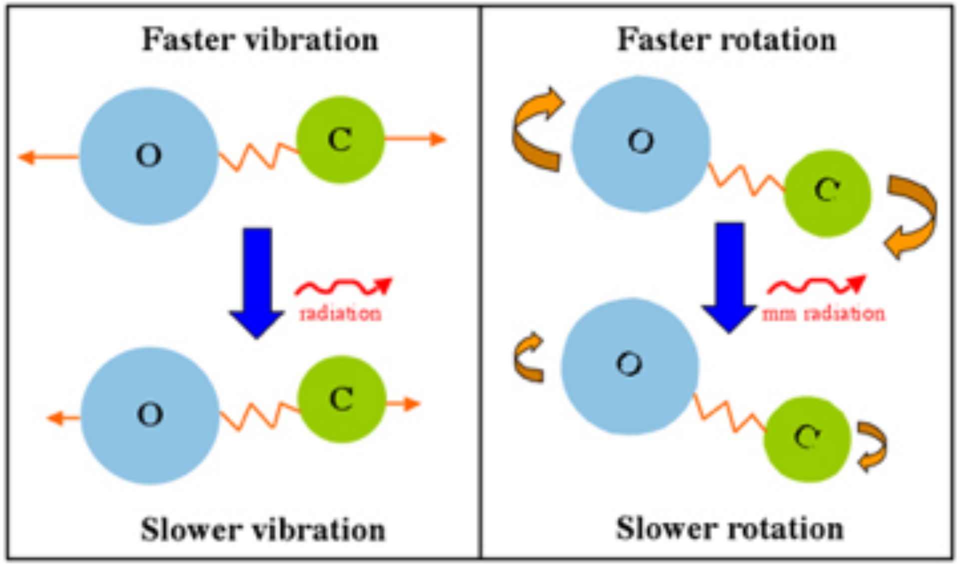
7.20 μm
赤外不活性

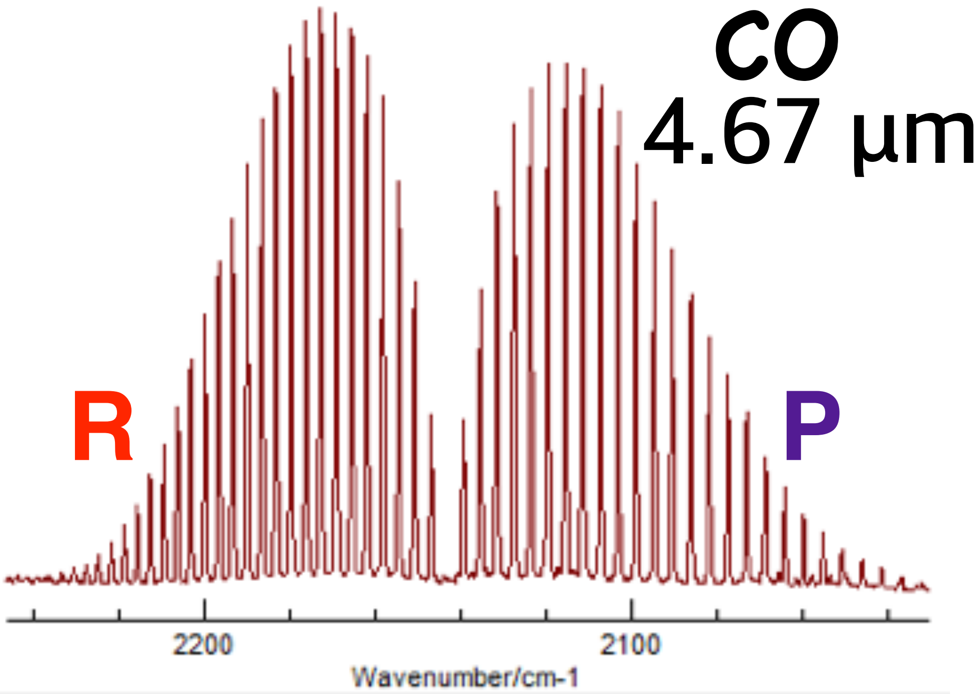
15.0 μm

4.26 μm

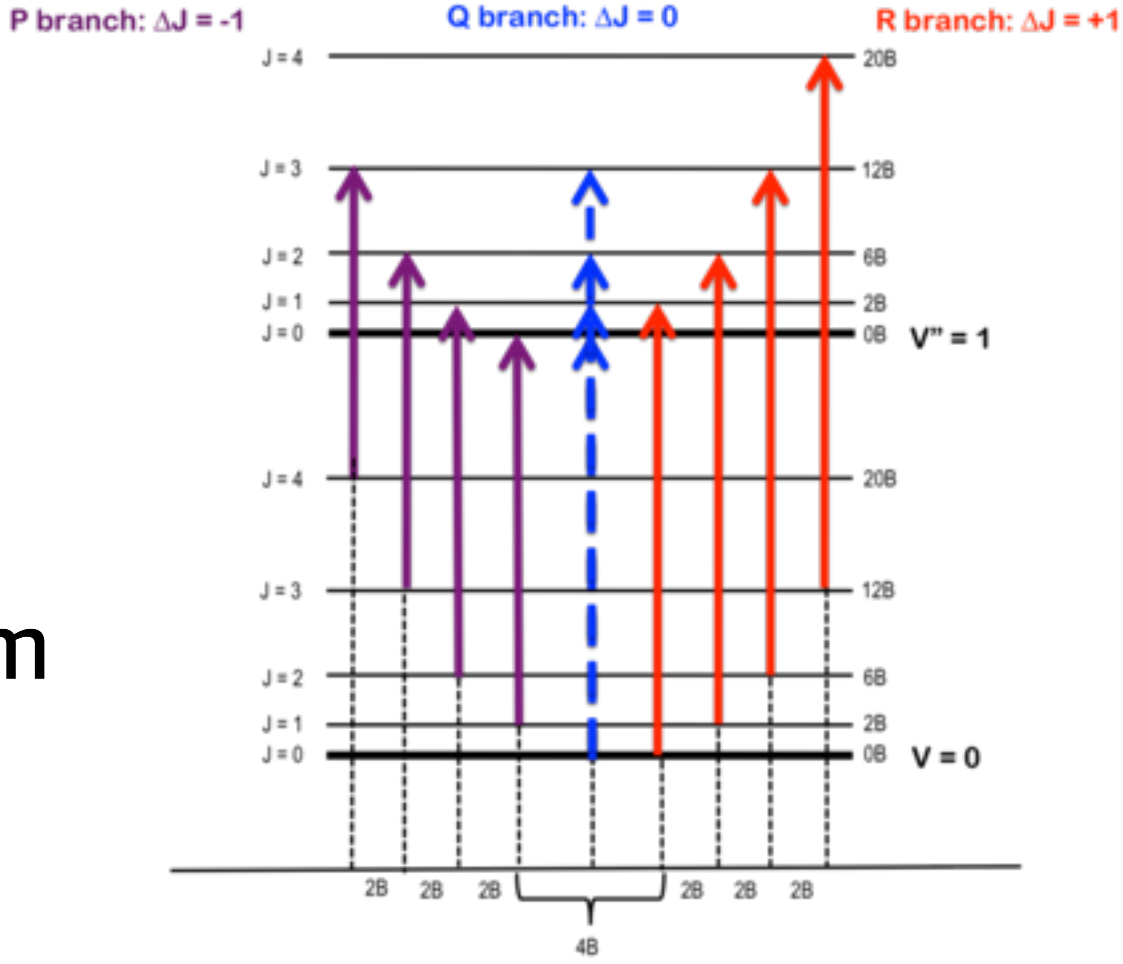
CO_2

分子の振動モード（近赤外線）



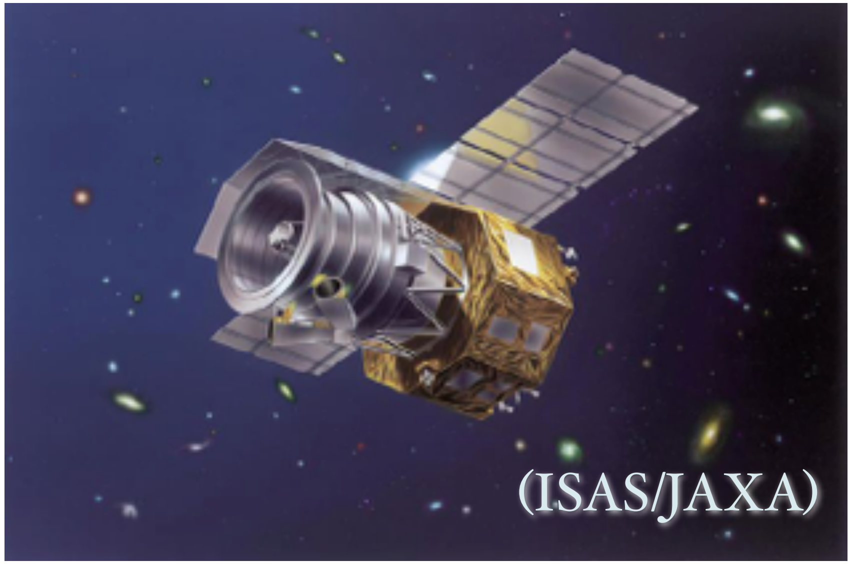


CO
4.67 µm

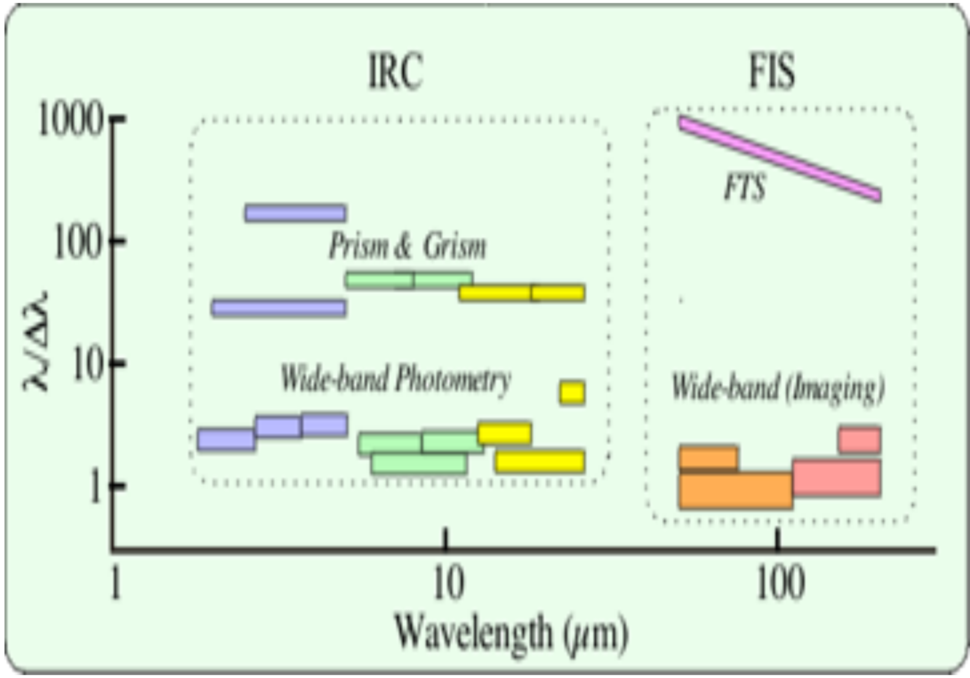


http://astronomy.swin.edu.au/cosmos/
https://chem.libretexts.org/

AKARI


(ISAS/JAXA)

- Japanese infrared satellite
- launched on Feb 22, 2006 (JST)
- Two focal-plane instruments
  - Far-Infrared Surveyor (FIS)
  - Infrared Camera (IRC)
- All-sky observations until August 2007 (> 1 year)
- Near-IR spectroscopic observations of comets were conducted in Phase 3
- phase 3: only near-IR instrument is available.



Observations - target comets

(Jupiter-family or Ecliptic comets)

Object	UT Date	r_h [AU]	Δ [AU]
19P/Borrelly	Dec 30.1 2008	2.19	1.95
22P/Kopff	Apr 22.6 2009	1.61	1.26
22P/Kopff	Apr 22.6 2009	1.61	1.26
22P/Kopff	Dec 11.2 2009	2.42	2.22
22P/Kopff	Dec 11.5 2009	2.43	2.22
22P/Kopff	Dec 11.5 2009	2.43	2.22
29P/S-W 1	Nov 18.5 2009	6.17	6.09
29P/S-W 1	Nov 18.6 2009	6.18	6.09
64P/S-G	Nov 23.1 2009	2.27	2.05
64P/S-G	Nov 23.2 2009	2.27	2.05
67P/C-G	Nov 2.4 2008	1.84	1.56
81P/Wild 2	Dec 14.1 2009	1.74	1.44
81P/Wild 2	Dev 14.2 2009	1.74	1.44
81P/Wild 2	Dec 14.5 2009	1.74	1.43
88P/Howell	Jul 3.1 2009	1.74	1.41
88P/Howell	Jul 3.1 2009	1.73	1.41
116P/Wild 4	May 15.6 2009	2.22	1.98
116P/Wild 4	May 16.5 2009	2.22	1.99
118P/S-L 4	Sep 8.7 2009	2.18	1.93
118P/S-L 4	Sep 8.8 2009	2.22	1.99
144P/Kushida	Apr 18.5 2009	1.70	1.37
144P/Kushida	Apr 18.6 2009	1.70	1.37
157P/Tritton	Dec 30.1 2009	1.48	1.11
157P/Tritton	Dec 30.3 2009	1.48	1.11

(Oort cloud comets)

Object	UT Date	r_h [AU]	Δ [AU]
C/2006 OF2 (Broughton)	Sep 16.7 2008	2.43	2.21
C/2006 OF2 (Broughton)	Mar 28.1	3.20	3.04
C/2006 Q1 (McNaught)	Jun 3.6 2008	2.78	2.59
C/2006 Q1 (McNaught)	Feb 23.8 2009	3.64	3.50
C/2006 W3 (Christensen)	Dec 21.1 2008	3.66	3.52
C/2006 W3 (Christensen)	Jun 16.8 2009	3.13	2.96
C/2007 G1 (LINEAR)	Aug 20.2 2008	2.80	2.62
C/2007 N3 (Lulin)	Feb 5.6 2009	1.28	0.80
C/2007 N3 (Lulin)	Mar 30.7 2009	1.70	1.36
C/2007 Q3 (Siding Spring)	Mar 3.3 2009	3.29	3.14
C/2008 Q3 (Garrad)	Jul 5.6 2009	1.81	1.48
C/2008 Q3 (Garrad)	Jul 6.5 2009	1.81	1.50
C/2008 Q3 (Garrad)	Jan 3.1 2010	2.96	2.78

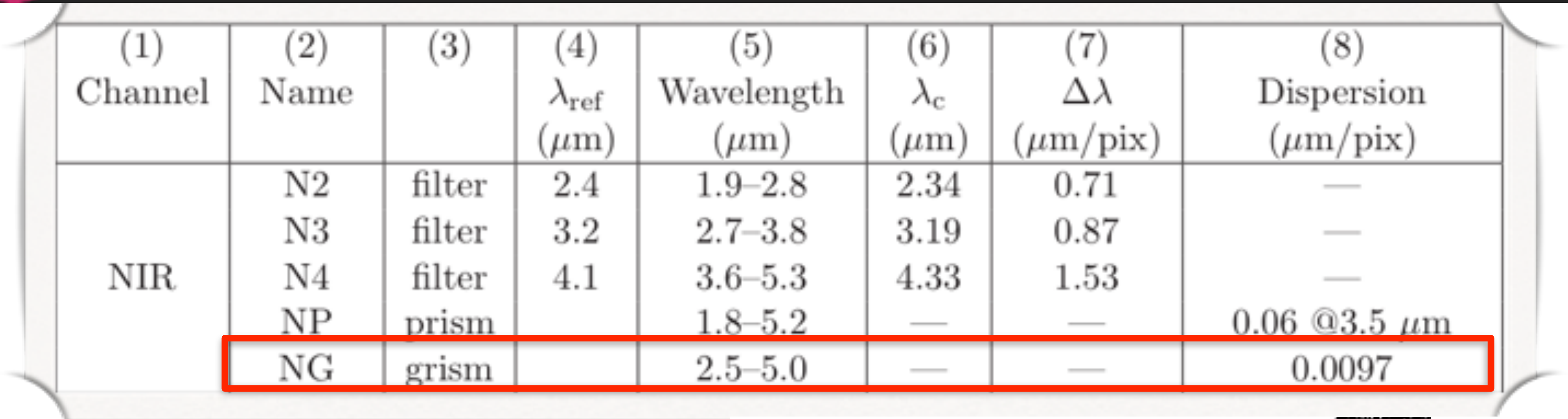
18 comets

37 detections in Phase 3

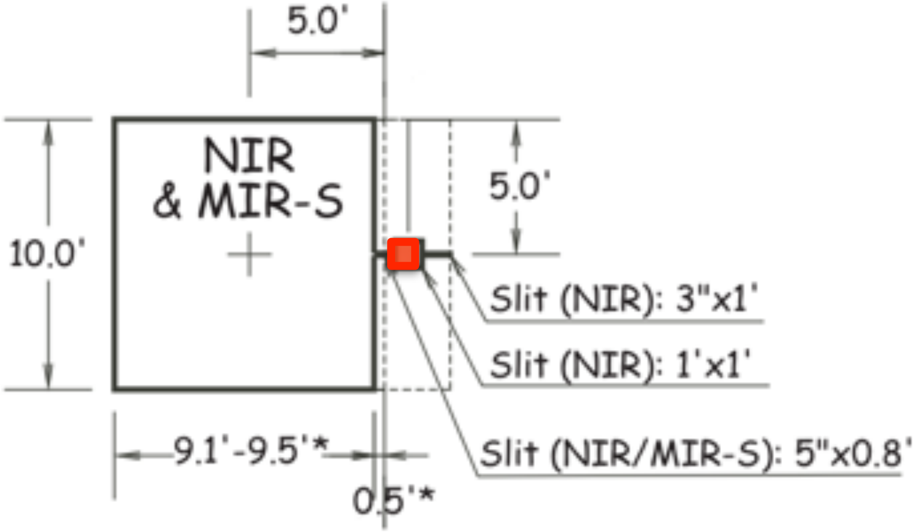
- **IRCZ4 NG(b;Np)** only here

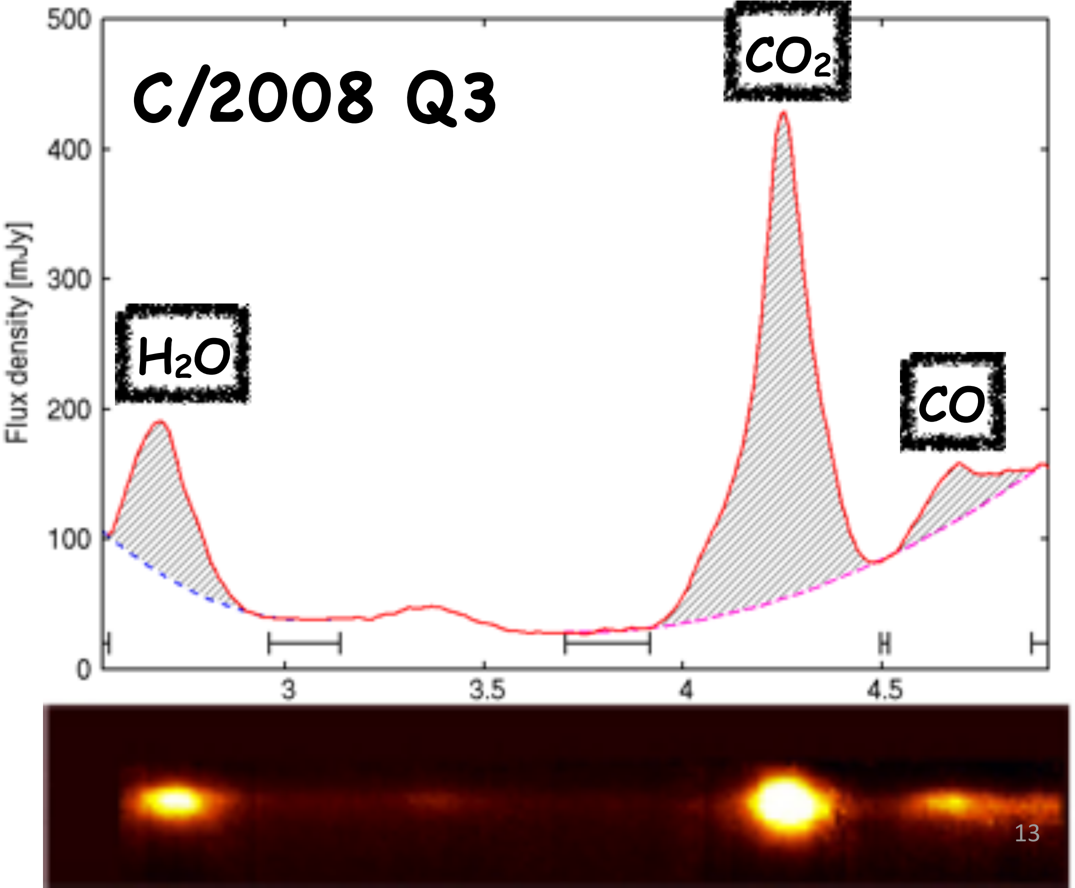
2008 Jun. -- 2010 Jan.

Observations - AKARI/IRC



(1) Channel	(2) Name	(3)	(4) $\lambda_{\rm ref}$ (μm)	(5) Wavelength (μm)	(6) λ_c (μm)	(7) $\Delta\lambda$ (μm/pix)	(8) Dispersion (μm/pix)
NIR	N2	filter	2.4	1.9–2.8	2.34	0.71	—
	N3	filter	3.2	2.7–3.8	3.19	0.87	—
	N4	filter	4.1	3.6–5.3	4.33	1.53	—
	NP	prism		1.8–5.2	—	—	0.06 @3.5 μm
	NG	grism		2.5–5.0	—	—	0.0097





Gas production rate of H_2O, CO_2, & CO

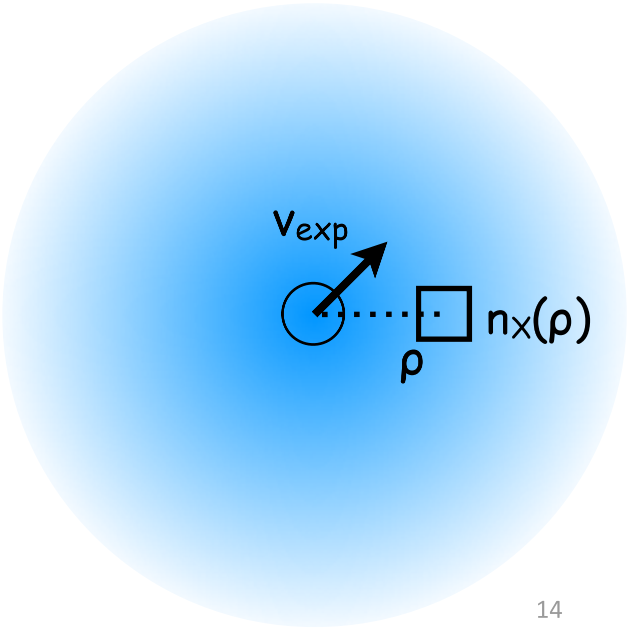
We assume optically thin conditions

Observed flux of molecule "X"(H_2O, CO_2, CO) is proportinal to the product of the g-factors (fluorescence efficiency) and the column density integrated within the aperture.

$$F_{\mathrm{obs}\_x} = \text{g-factor}_x * N_x$$

Column density of X is calculated by integrating below number density along the line-of-sight. Number density of the molecule X (n_x [/km^3]) is written as follow;

$$n_{\mathrm{X}}(\rho) = \frac{Q(\mathrm{X})}{4\pi v_{\mathrm{exp}}\rho^2} \exp\left(-\frac{\rho}{v_{\mathrm{exp}}\tau_{\mathrm{X}}}\right)$$



Q_x : production rate of the molecule X [molecules/s]

v_{exp} : expansion velocity of the gas ($0.8 \times r_h^{-0.5}$ [km/s])

ρ : nucleocentric distance [km]

τ_x : photo-dissociation lifetime of the molecule X [s]

g-factor

We assume optically thin conditions

$$F_{\mathrm{obs}\_x} = g\text{-factor}_x * N_x$$

g-factor:

$$g_x = (1/8\pi h \sigma_x \omega_x)\, A_{x,0}\, J(\sigma_x)$$

(Crovisier+ 1987)

$J(\sigma_x)$: Solar field density at the band wavenumber
ω_x: the band degeneracy
$A_{x,0}$: the equivalent Einstein coefficient

g-factor and photodissociation rate

CO_2

g-factor:

2.6e-3 /sec (4.26 μm, quiet Sun at 1au)

photodissociation rate:

2.0e-6 /sec (quiet Sun at 1au)
6.5e-10 — 1.4e-9 /sec (interstellar)

CO

g-factor:

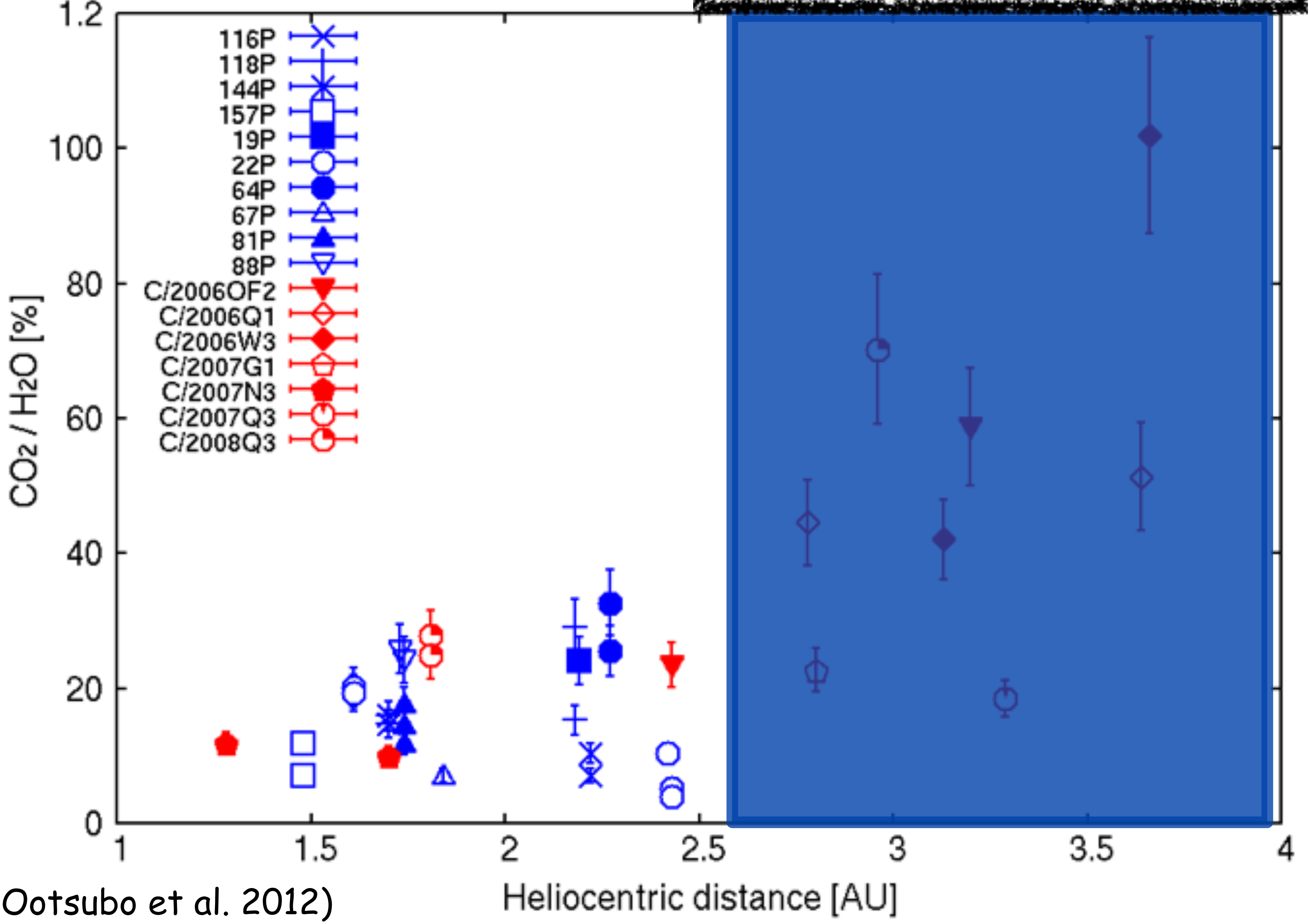
2.6e-4 /sec (4.67 μm, quiet Sun at 1au)

photodissociation rate:

7.5e-7 — 1.2e-6 /sec (quiet Sun at 1au)
1.8e-10 /sec (interstellar)

Results of CO_2 Mixing Ratio

(gas production rate ratio CO_2/H_2O)

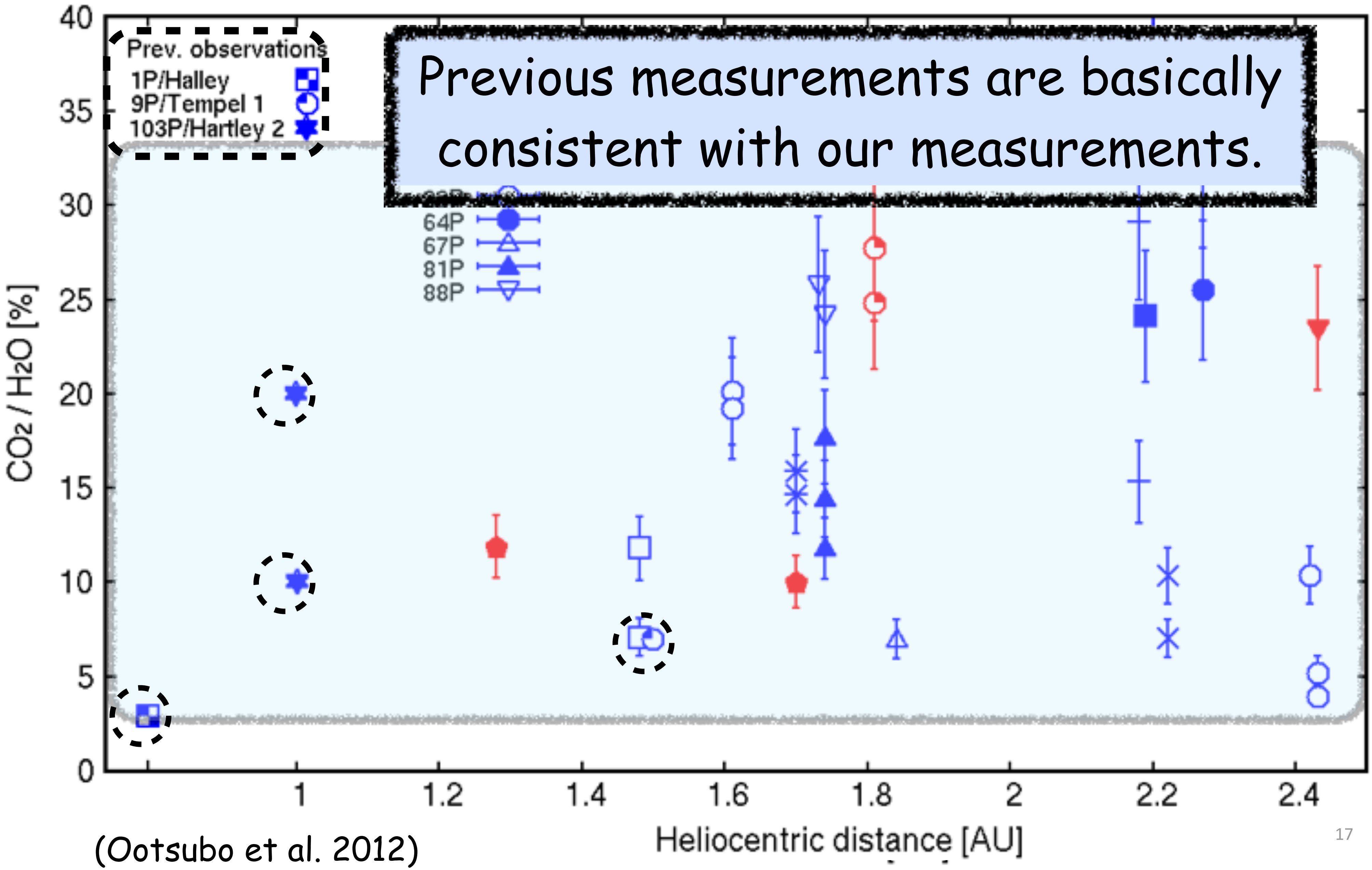


insufficient H_2O sublimation

(Ootsubo et al. 2012)

Results of CO_2 Mixing Ratio

(gas production rate ratio CO_2/H_2O)

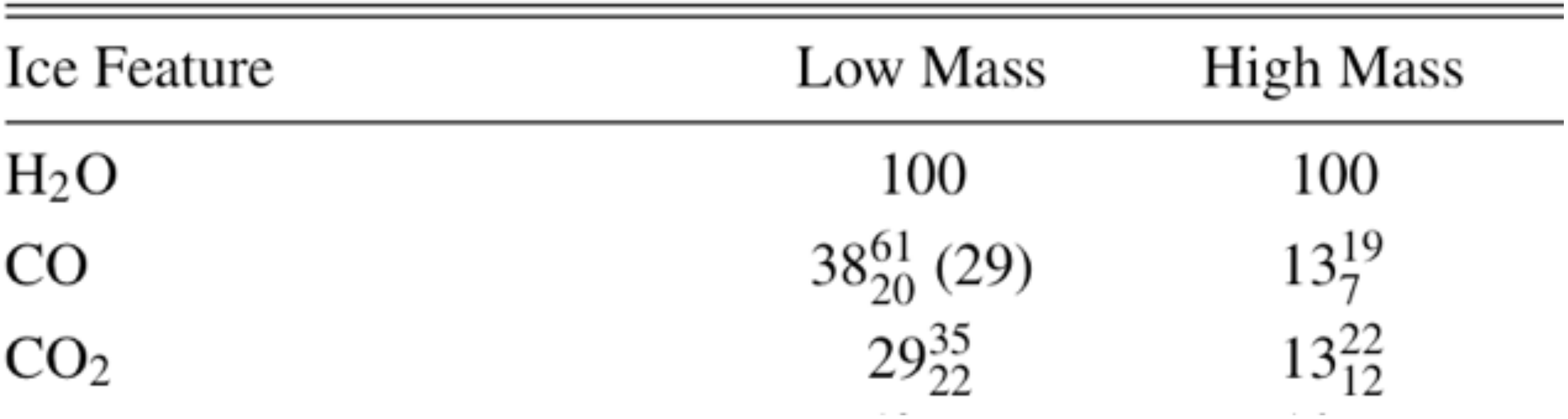


Previous measurements are basically consistent with our measurements.

(Ootsubo et al. 2012)

Comparison with interstellar ices

Abundance Medians and Lower and Upper Quartile Values of Ices with Respect to Water ice (Oberg et al. 2011)



Ice Feature	Low Mass	High Mass
H_2O	100	100
CO	38_{20}^{61} (29)	13_{7}^{19}
CO_2	29_{22}^{35}	13_{12}^{22}

CO_2/H_2O = 11%—24% (X_{median} = 17%)

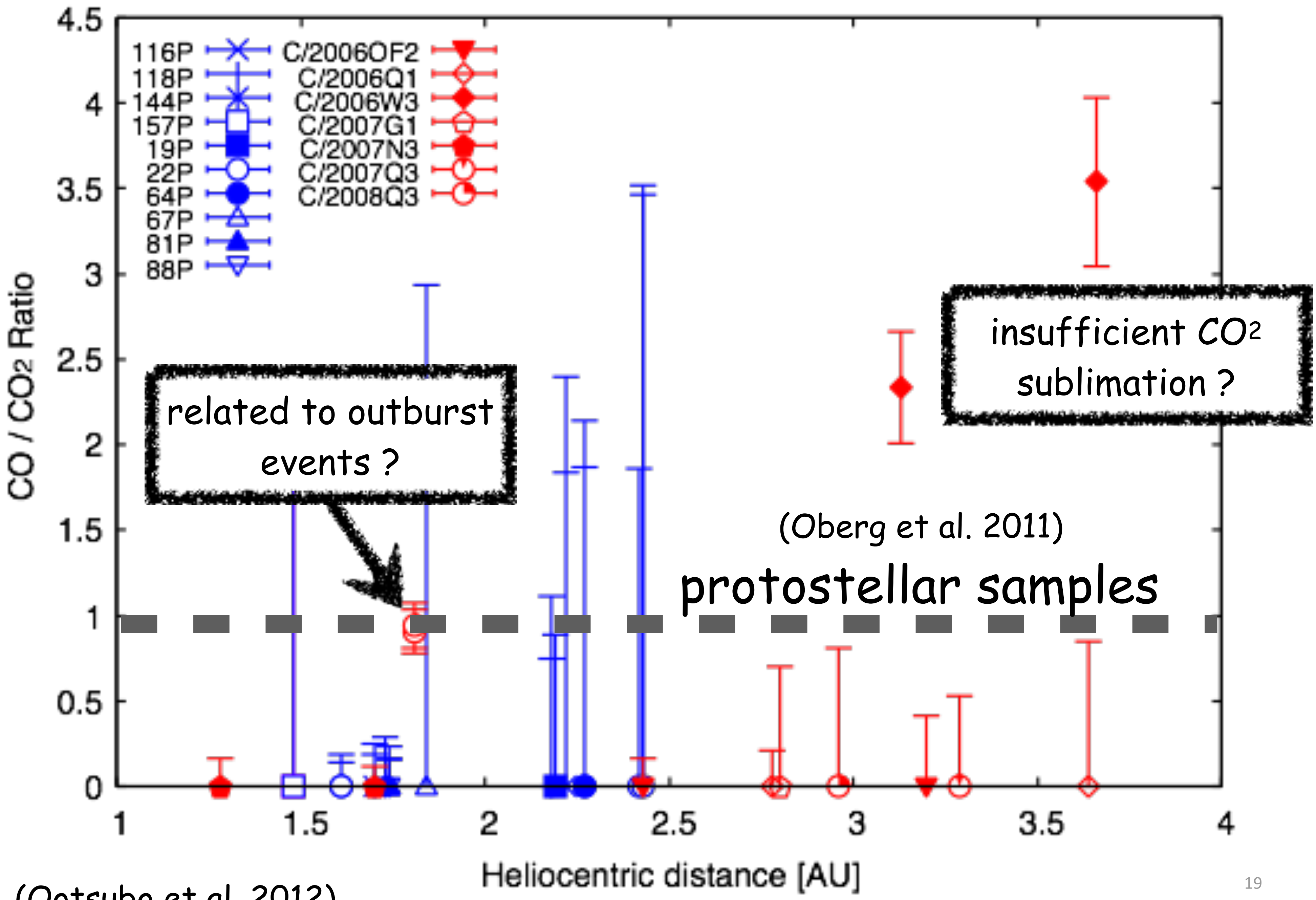
for AKARI comet samples

Comets < low-mass protostars

Comets ~ high mass protostars

Cometary ices were altered in the early solar nebula ?

CO/CO_2 ratio



related to outburst events ?

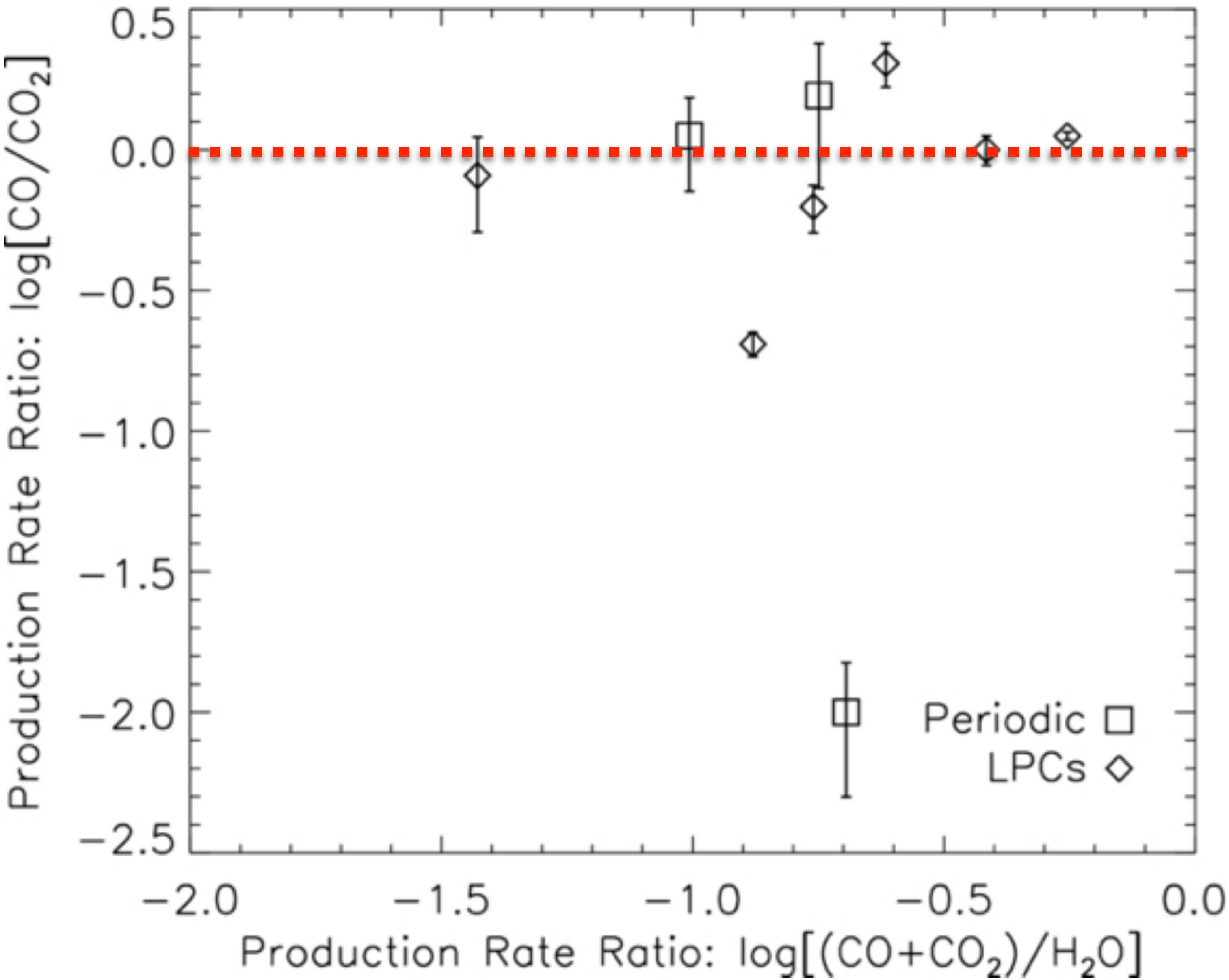
insufficient CO_2 sublimation ?

(Oberg et al. 2011)

protostellar samples

(Ootsubo et al. 2012)

CO/CO_2 ratio



(A'Hearn et al. 2012)

Summary for comet ice

✳We Observed **18 comets** in **near-IR (2.5–5 μm)** with AKARI/IRC.

✳The largest homogenous database of cometary CO_2 obtained so far.

✳AKARI/IRC detected cometary **H_2O, CO_2 and CO** simultaneously.

CO_2

detected in **17** out of the 18 samples (except 29P/SW1 at 6 AU)

CO_2/H_2O ratios show < **4--30 %** in our samples

CO

detected in only **3** comets (29P, C/2006 W3, C/2008 Q3)
only upper limits of CO/H_2O ratios in most of our samples

∗**CO_2/H_2O ratio in comets is**

- **consistent with comets observed previously**
- **more depleted and diverse than low-mass protostellar ices**

Summary for comet ice

✳ 彗星でも CO, CO_2 が両方検出されている観測例はまだ少ない

✳ CO 強度が強い彗星でも CO/CO_2 の値は ~ 1.0 (0.5–2.0)

✳ CO/CO_2 は、彗星の type (OCs, JFCs) による大きな差は見られない

✳ 原始太陽系円盤中での彗星核の形成場所は、まだ不定性が大きいが
ざっくり 5–35 au

✳ 彗星の CO/CO_2 の値は、太陽 (G2V) 系の5-35 au 付近の結果
であることに注意

彗星ケイ酸塩ダストの
中間赤外線観測

大坪貴文 (ISAS/JAXA), 本田充彦 (久留米大),
渡部潤一 (国立天文台),
河北秀世, 新中善晴 (京都産業大),
古荘玲子 (都留文科大), 臼井文彦 (神戸大)、他

彗星の中間赤外線分光観測

1970年 - Bennett彗星

- 10μm 超過を彗星で初めて検出

  --> シリケイト？

1986年 - Halley彗星

- 11.2μmのサブピークを検出

  (Bregman et al. 1987)

1987年 - Bradfield彗星

- 11.3μmのサブピーク

  結晶質olivine？

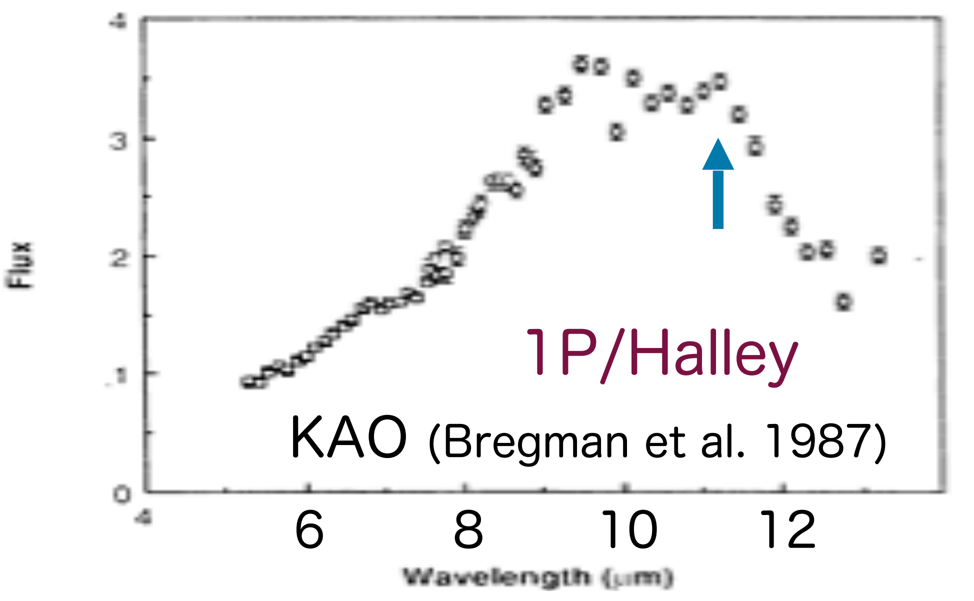
  (Hanner et al. 1990)

1997年 - Hale-Bopp彗星

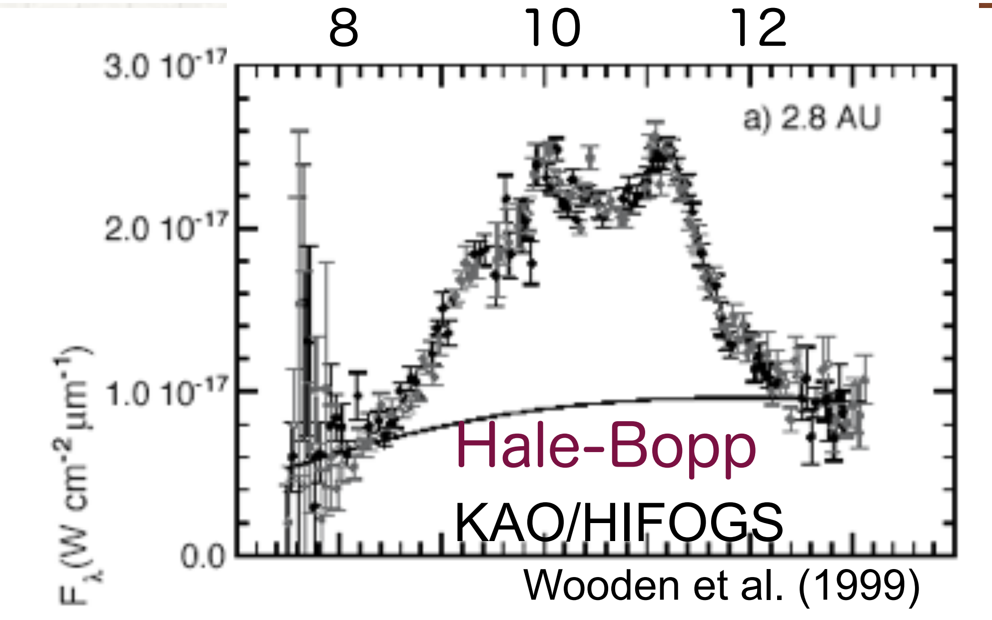
- 結晶質olivine＋pyroxene？

  ISO による赤外線スペクトル

  彗星ダスト研究の教科書的存在

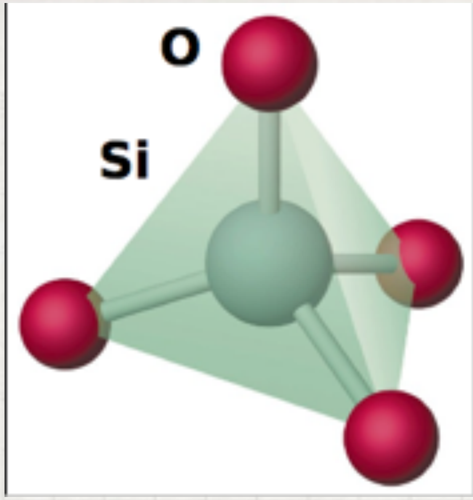


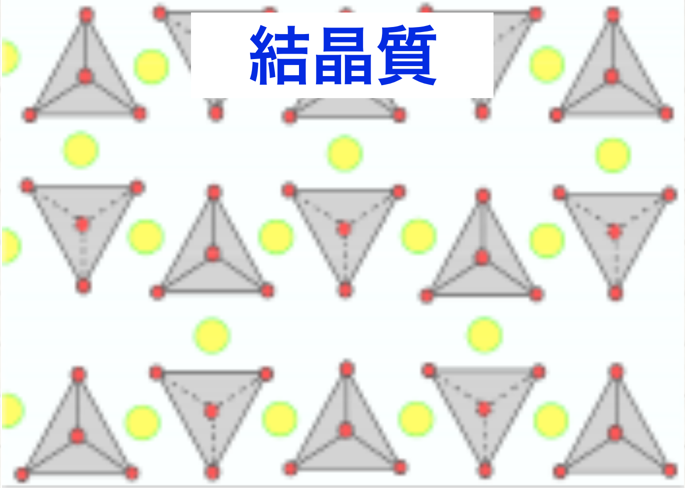
KAO (Bregman et al. 1987)

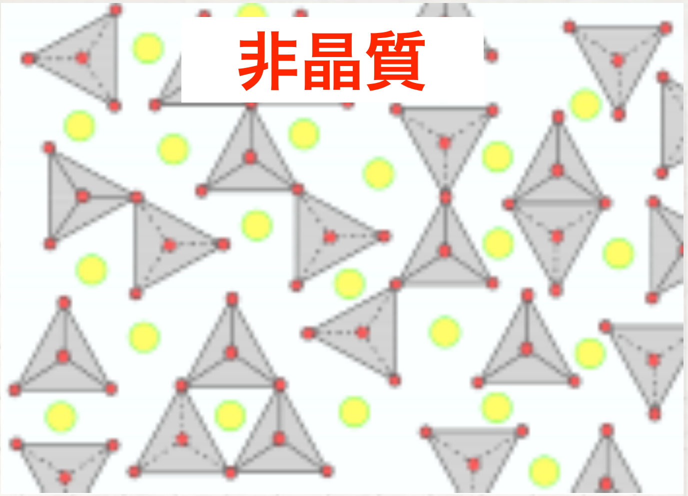


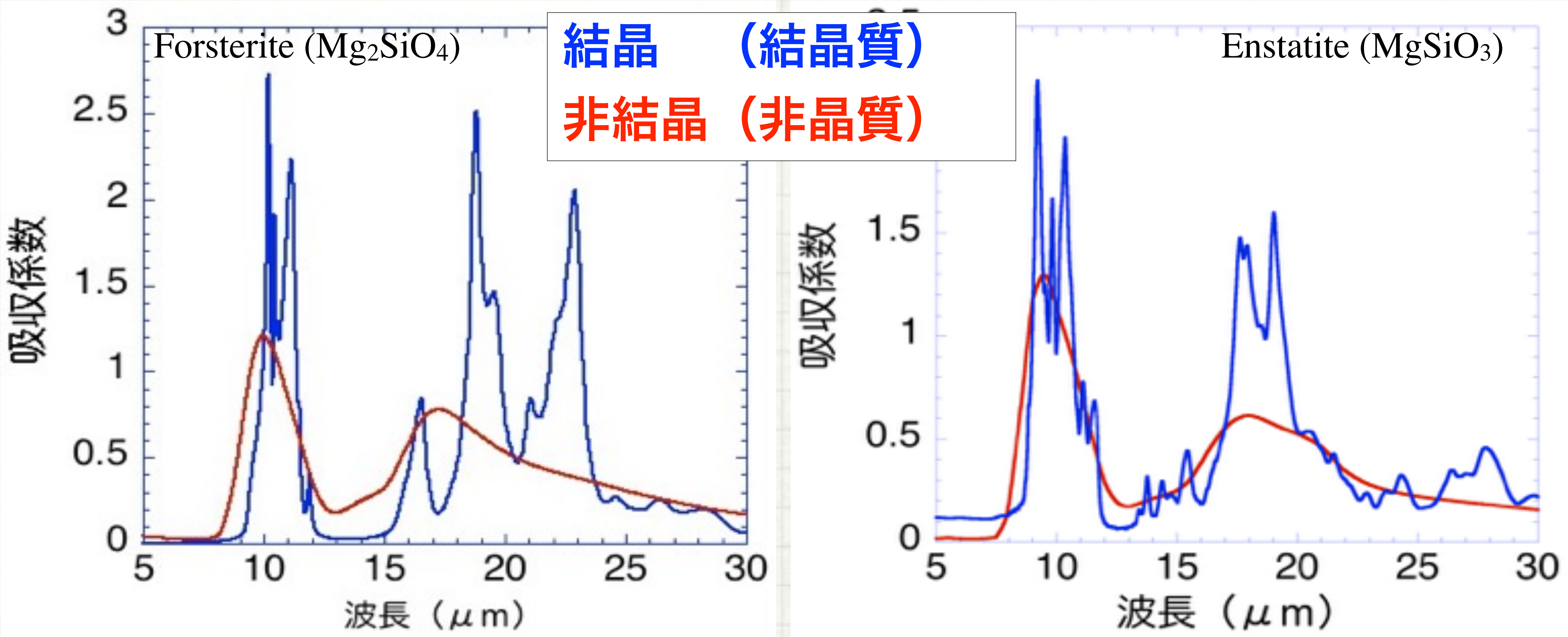
KAO/HIFOGS

Wooden et al. (1999)









- olivne（カンラン石）

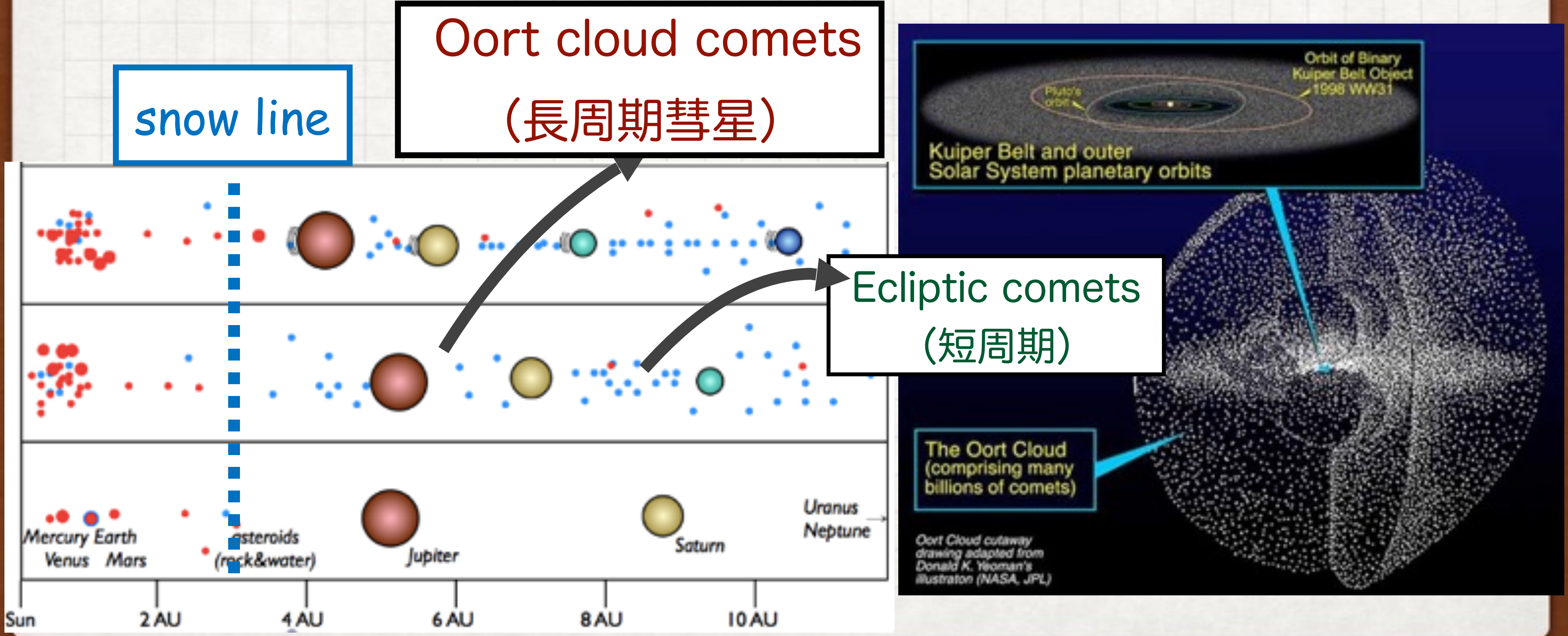
  $(Mg,Fe)_2SiO_4$

- pyroxene（輝石）

  $(Mg,Fe)SiO_3$

彗星中の結晶質シリケイト

- **彗星 - 氷＋塵 (dirty water-ice)**
  - 多くの彗星で結晶質シリケイトの存在が確認されている
  - 殆どは**低温凝縮物（$T < 150$ K）**である氷。星間塵は非晶質。
  - **高温生成物（$T > 800$K）**である結晶質シリケイトはどこから？
  - OCs（長周期）と ECs（短周期）の差は？



snow line

Oort cloud comets

（長周期彗星）

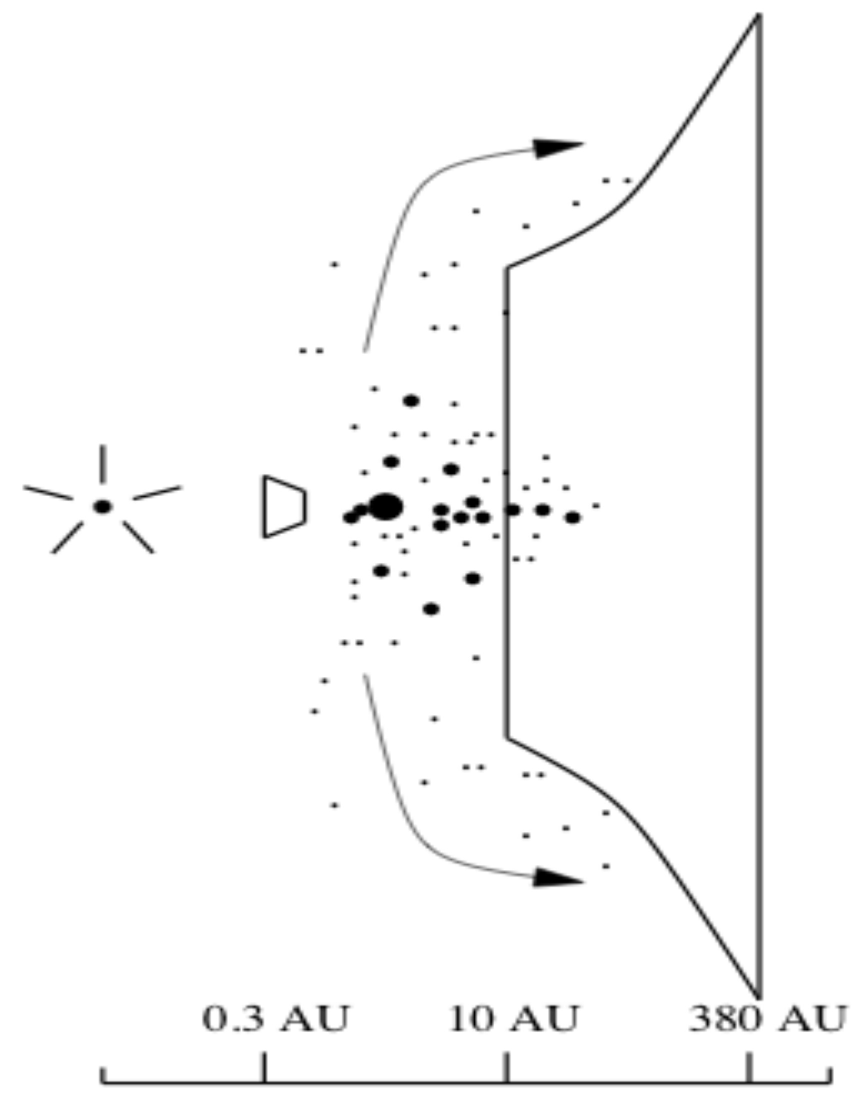
Ecliptic comets

（短周期）

Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustration (NASA, JPL)

彗星中の結晶質シリケイトの起源

★ 彗星塵は何らかの要因で内側の領域から運ばれた？



原始太陽系星雲の乱流輸送によって内側から外側へ

（Bockelee-Morvan et al. 2002）

微惑星衝突と原始木星による重力散乱で外側の領域へ

（Bouwman et al. 2003）

原始太陽からのOutflowによって内側から外側へ（X-wind）

（Shu et al. 1996）

Mid-IR observations of comets

彗星の中間赤外線分光観測

- すばる望遠鏡＋COMICS

  中間赤外線低分散分光 (8-13 μm; R～250)

- これまでに観測した彗星

Oort cloud comets

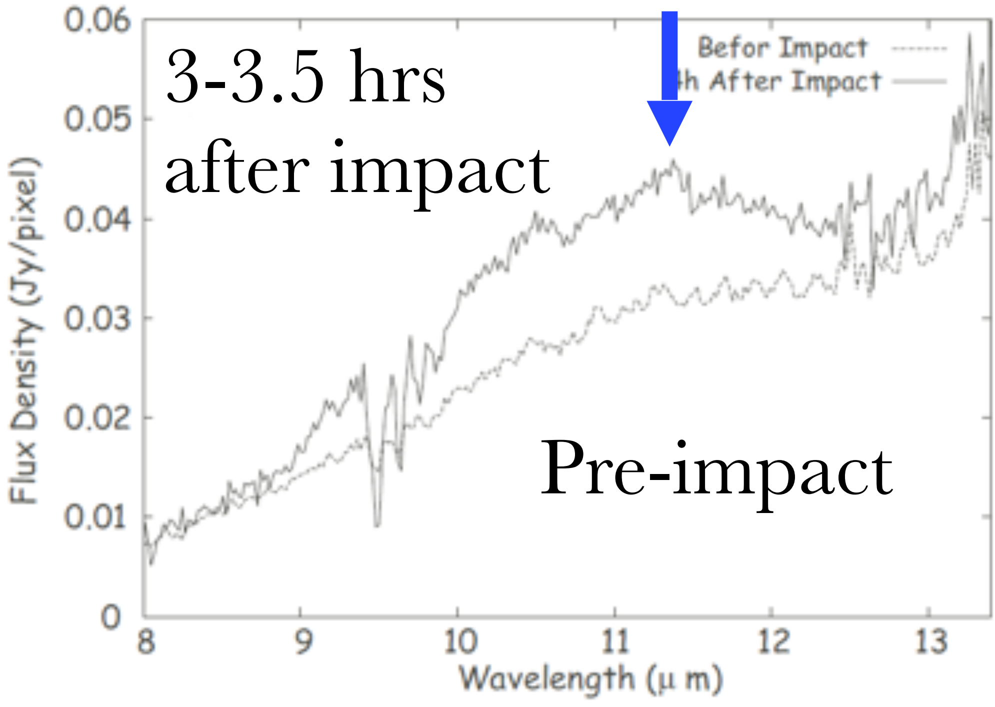
C/2001 Q4, C/2002 V1 (NEAT)
C/2001 RX14 (LINEAR)
C/2004 Q2 (Machholz)
C/2007 N3 (Lulin)

C/2012 S1 (ISON)
C/2013 R1 (Lovejoy)
C/2012 X1 (LINEAR)
C/2011 L4, C/2012 K1 (PanSTARRS)

Ecliptic comets

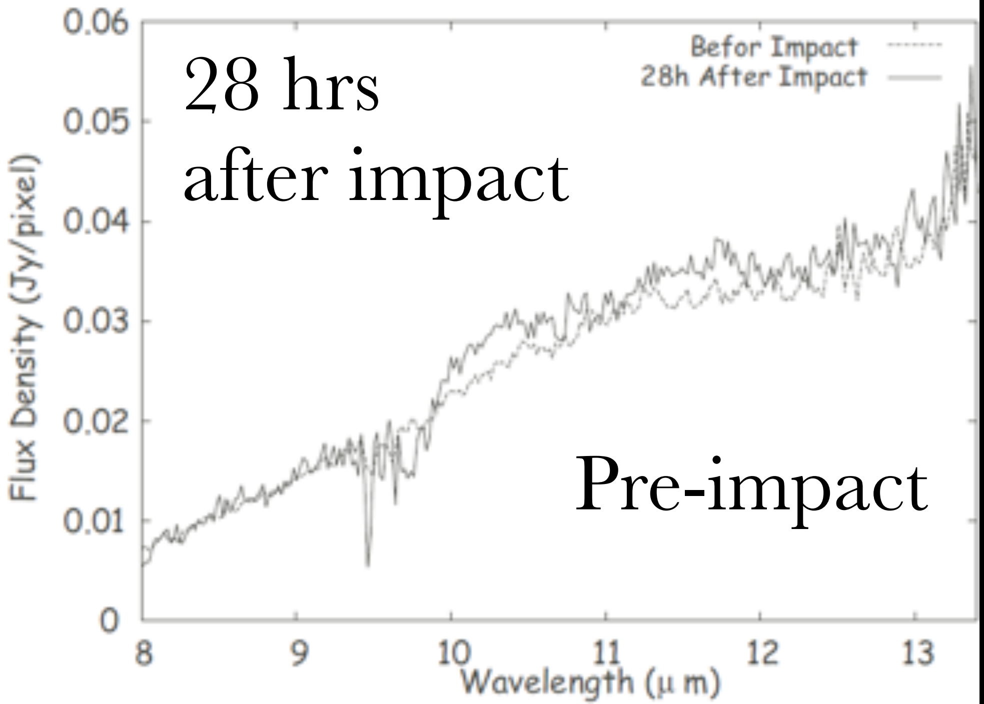
2P/Encke, 78P/Gehrels
9P/Tempel → Deep Impact
21P/Giacobini-Zinner
73P/Schwassmann-Wachmann

4P/Faye, 17P/Holmes, 8P/Tuttle
144P/Kushida
10P/Tempel, 103P/Hartley



3-3.5 hrs after impact

Pre-impact

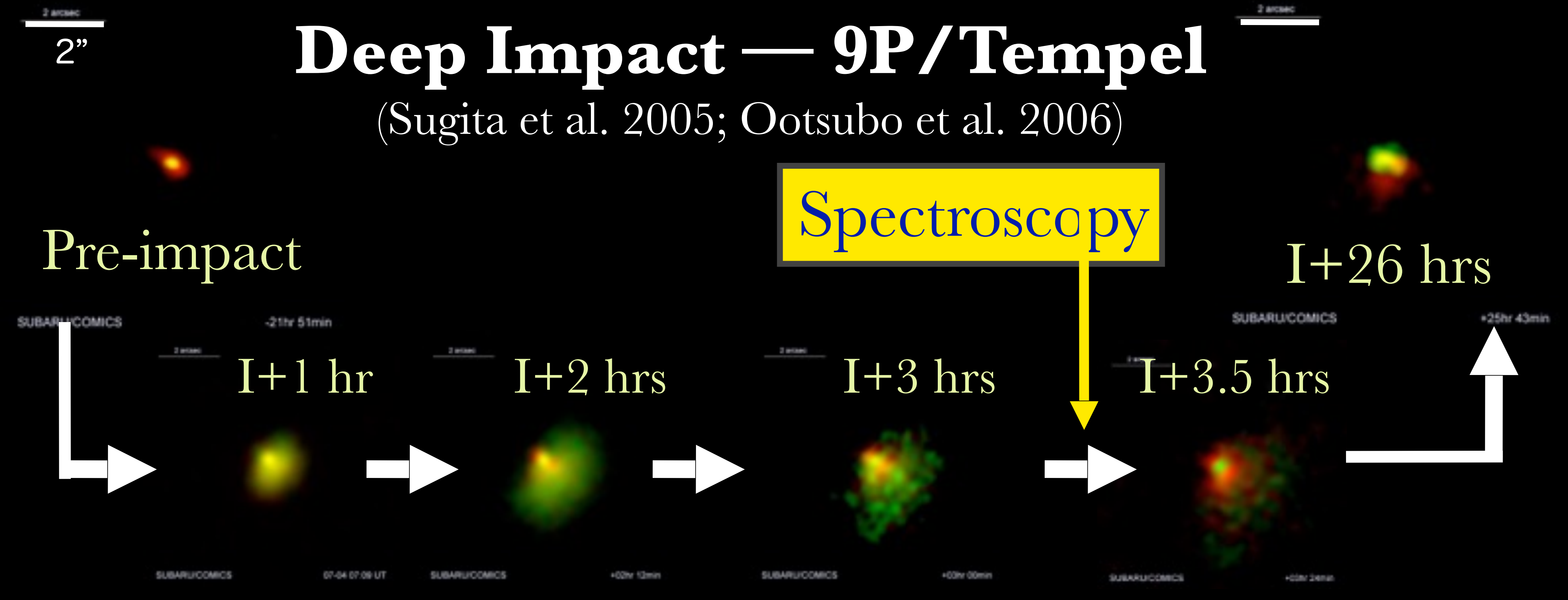


28 hrs after impact

Pre-impact

Deep Impact — 9P/Tempel

(Sugita et al. 2005; Ootsubo et al. 2006)



Spectroscopy

Pre-impact

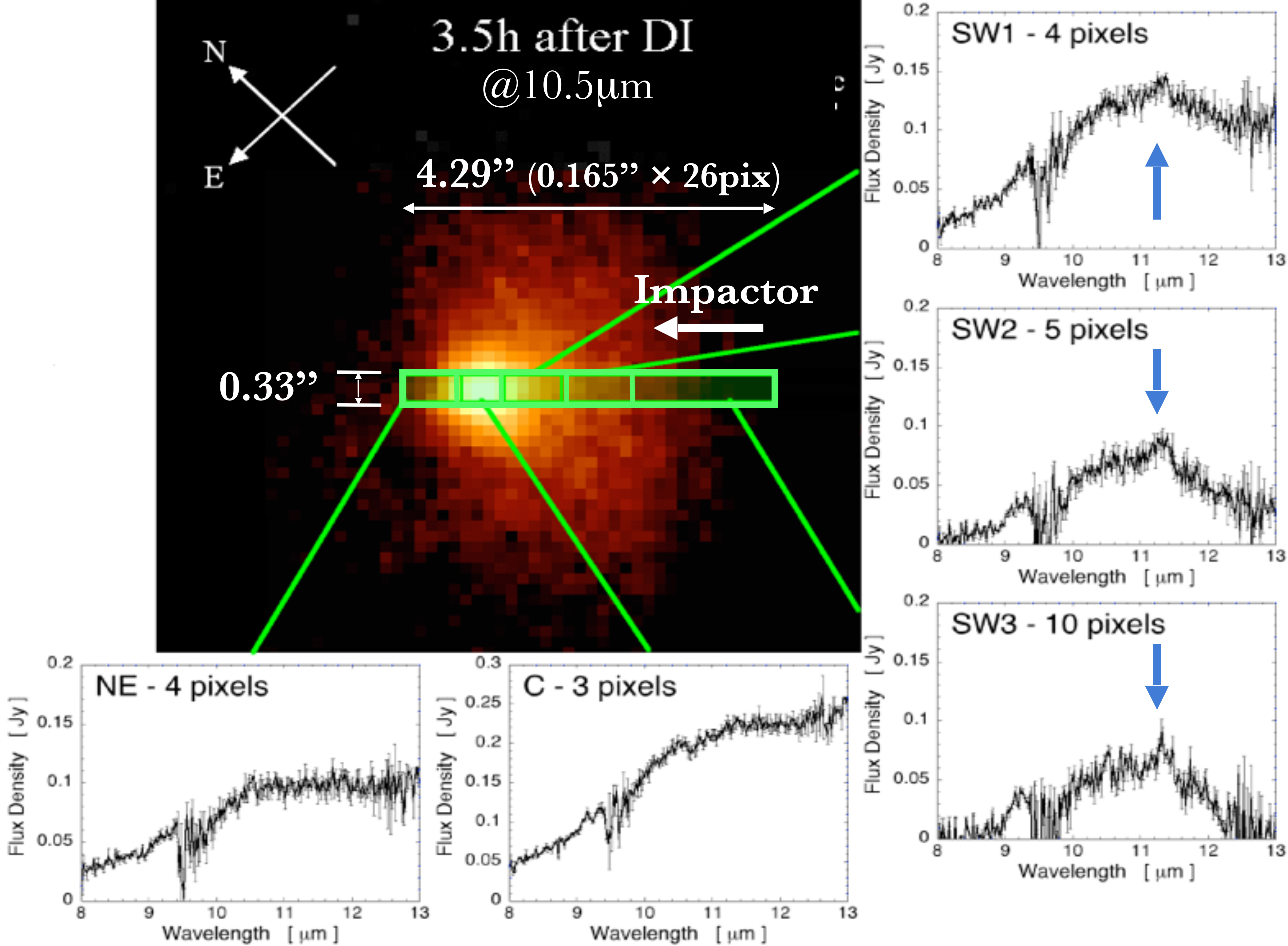
I+26 hrs

I+1 hr

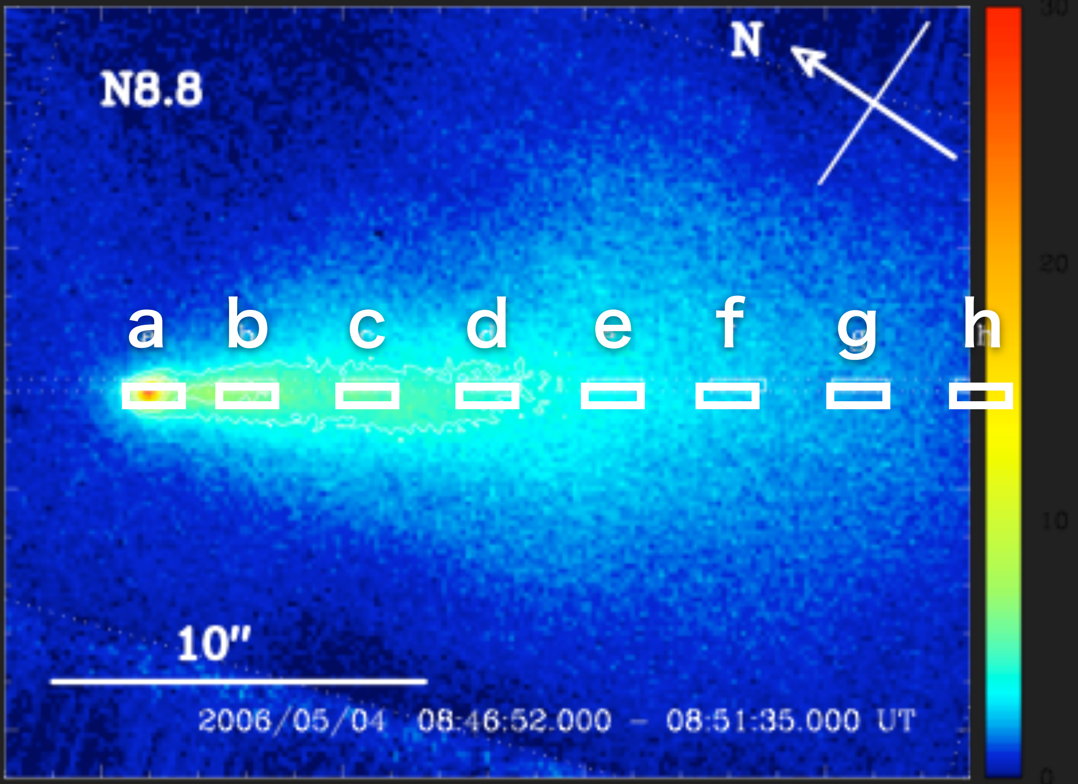
I+2 hrs

I+3 hrs

I+3.5 hrs



“Subaru/COMICS spectroscopy of 9P/Tempel” by T. Ootsubo, 7-10, 2006, Brussels, Belgium



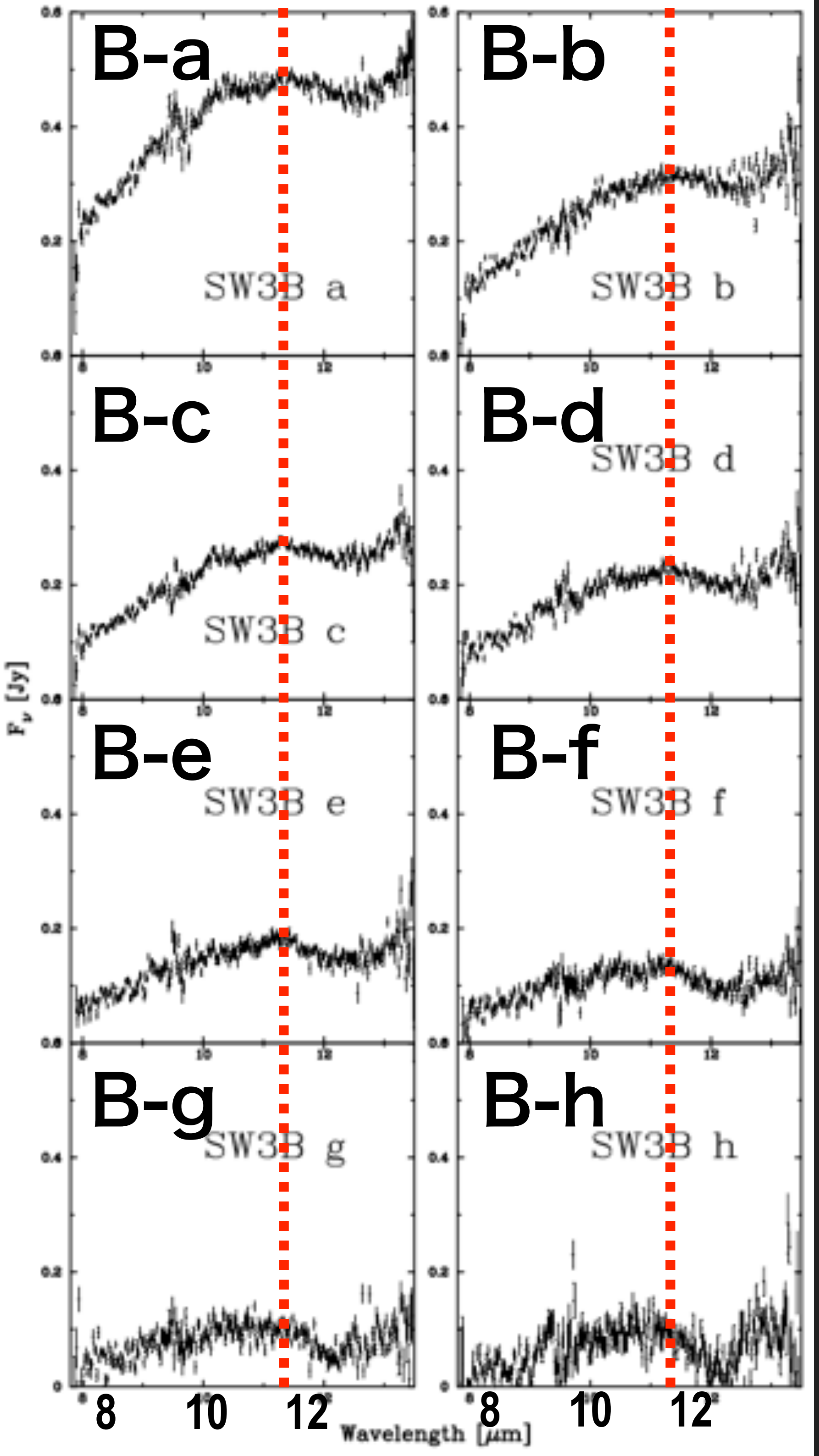
73P/SW - B

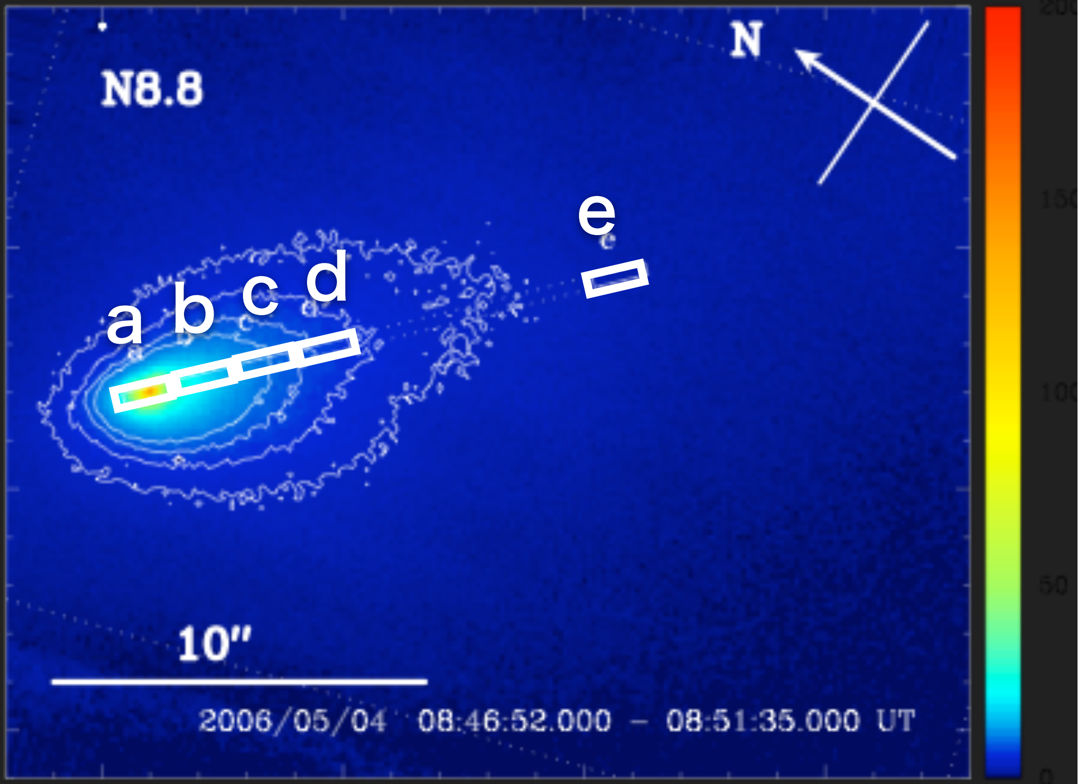
(2006/05/04UT)

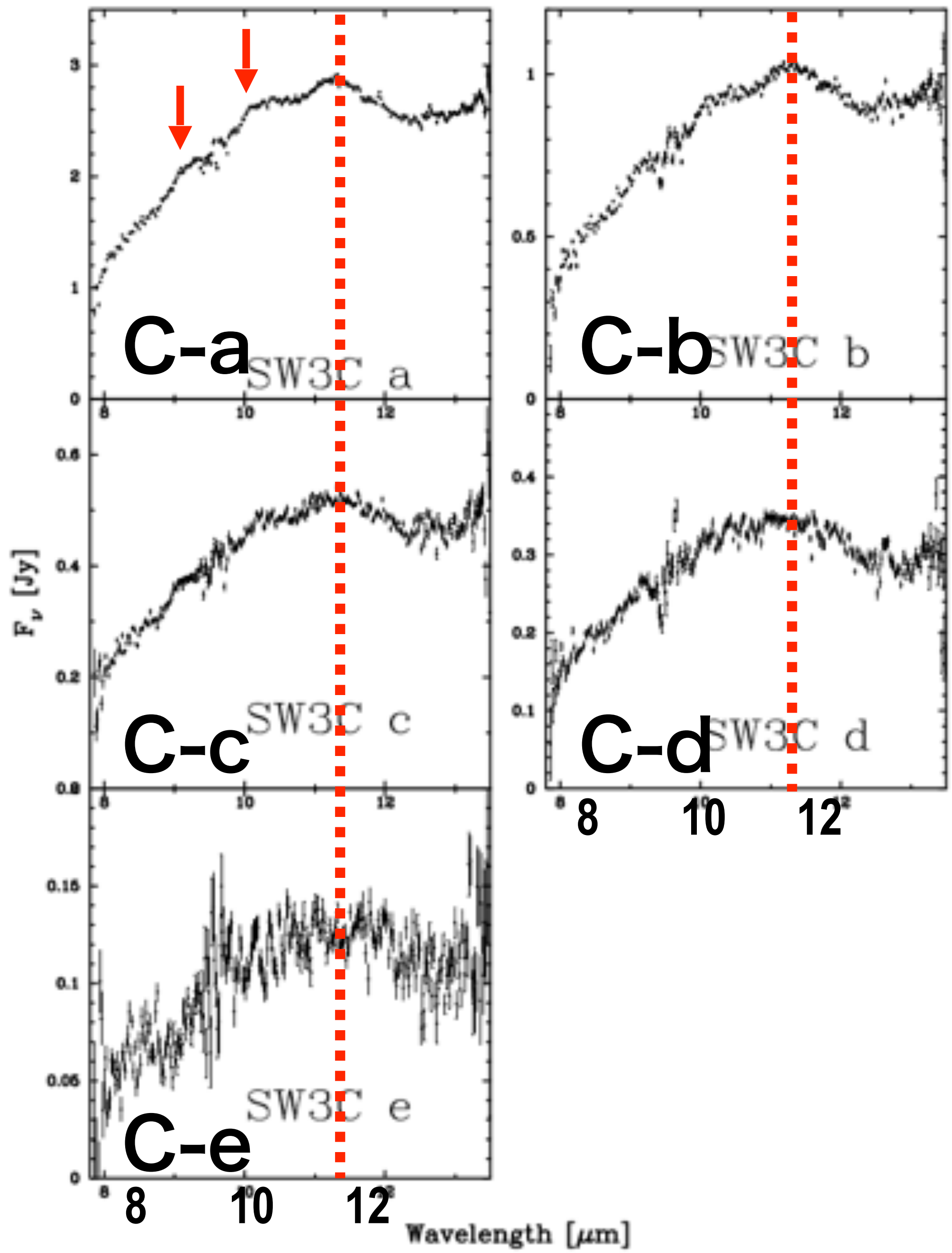
11.2 μm crystallin feature

fragmentation

(Watanabe et al. in prep.)







73P/SW - C

(2006/05/04UT)

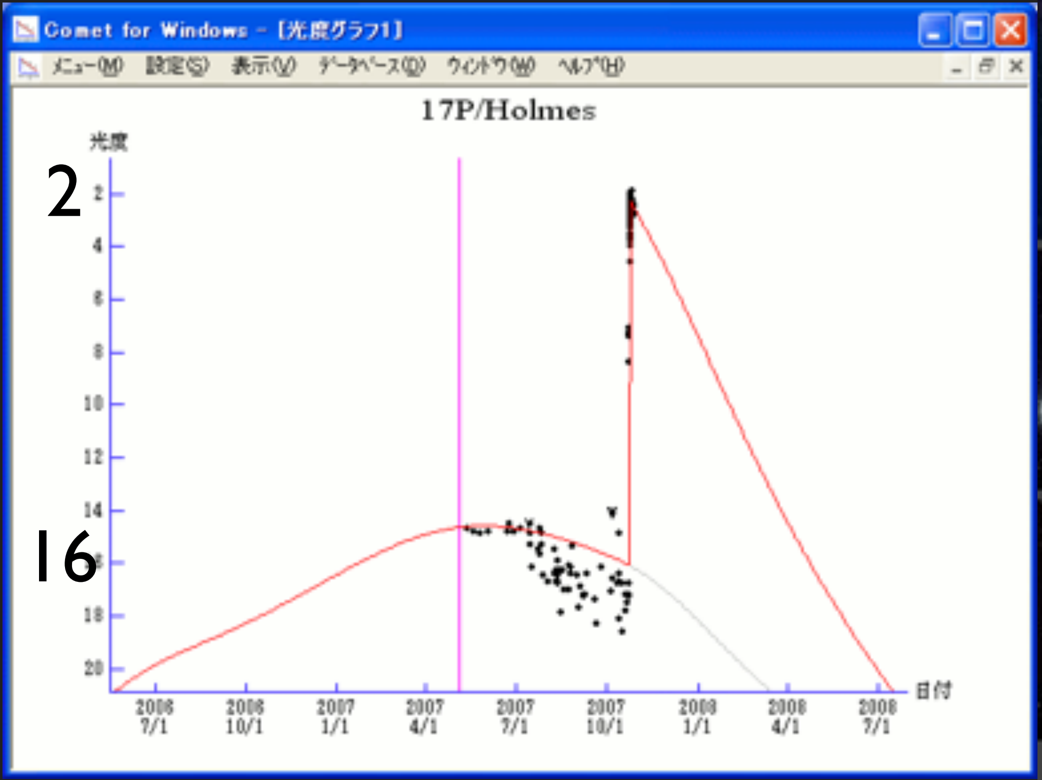
11.2 μm crystallin feature

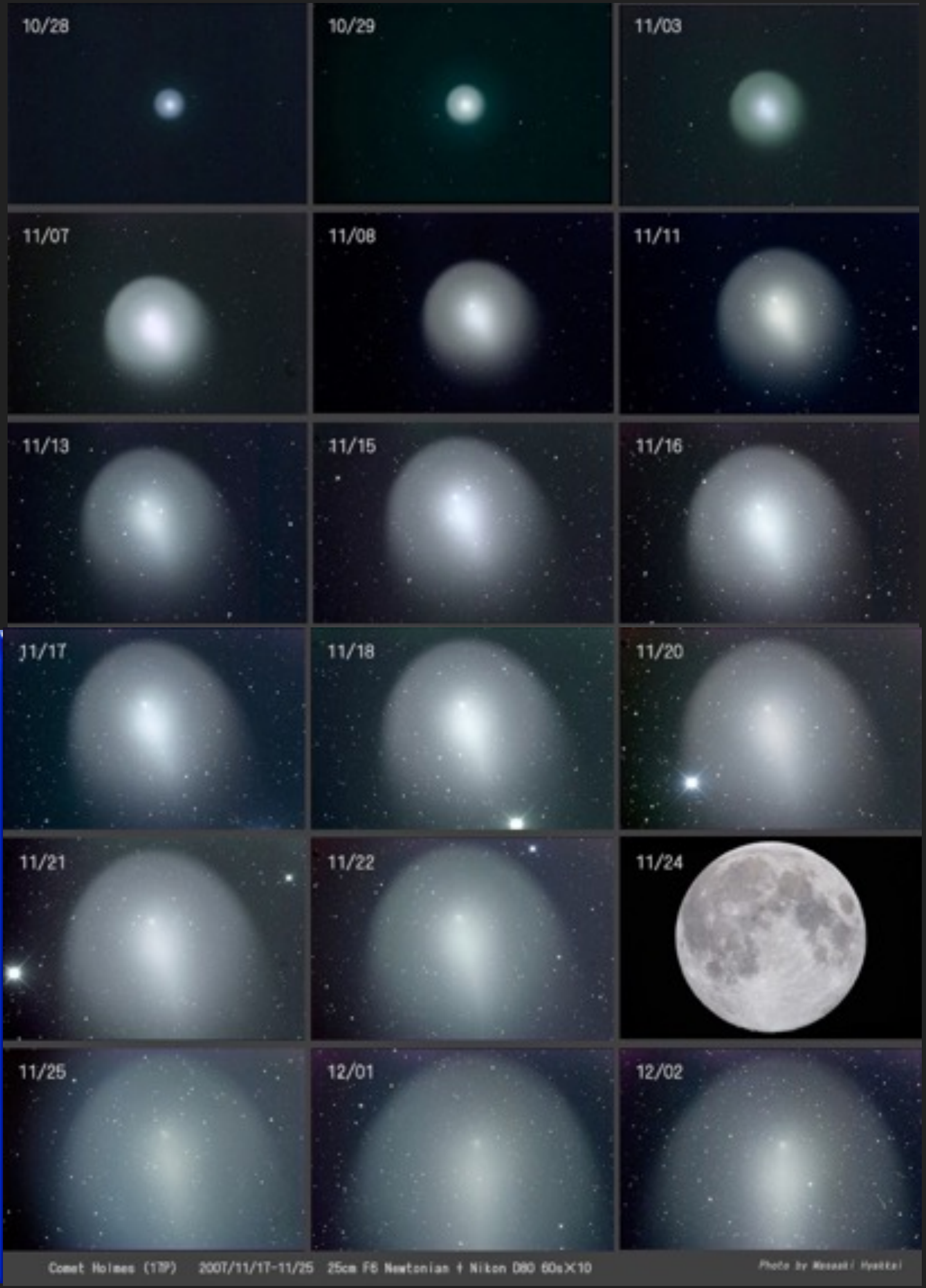
feature strength is larger than nucleus B

17P/Holmes

突然のアウトバースト
(2007/10/24UT)

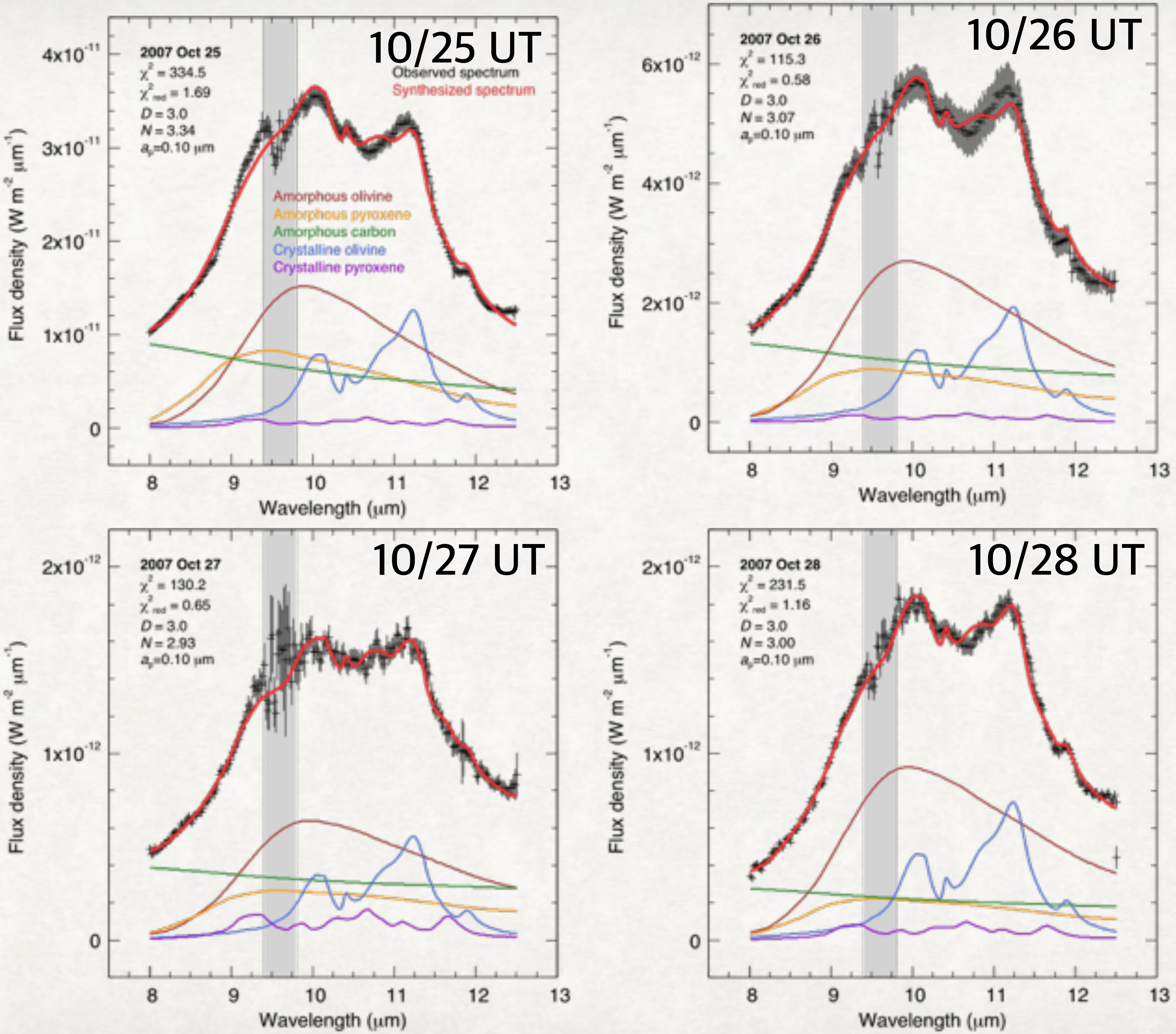
- 対称に広がる薄いコマ
- 彗星核から一方向に放出された塵雲





Comet Holmes (17P) 2007/11/17-11/25 25cm F6 Newtonian + Nikon D80 60s×10

Photo by Masaaki Hyakkai



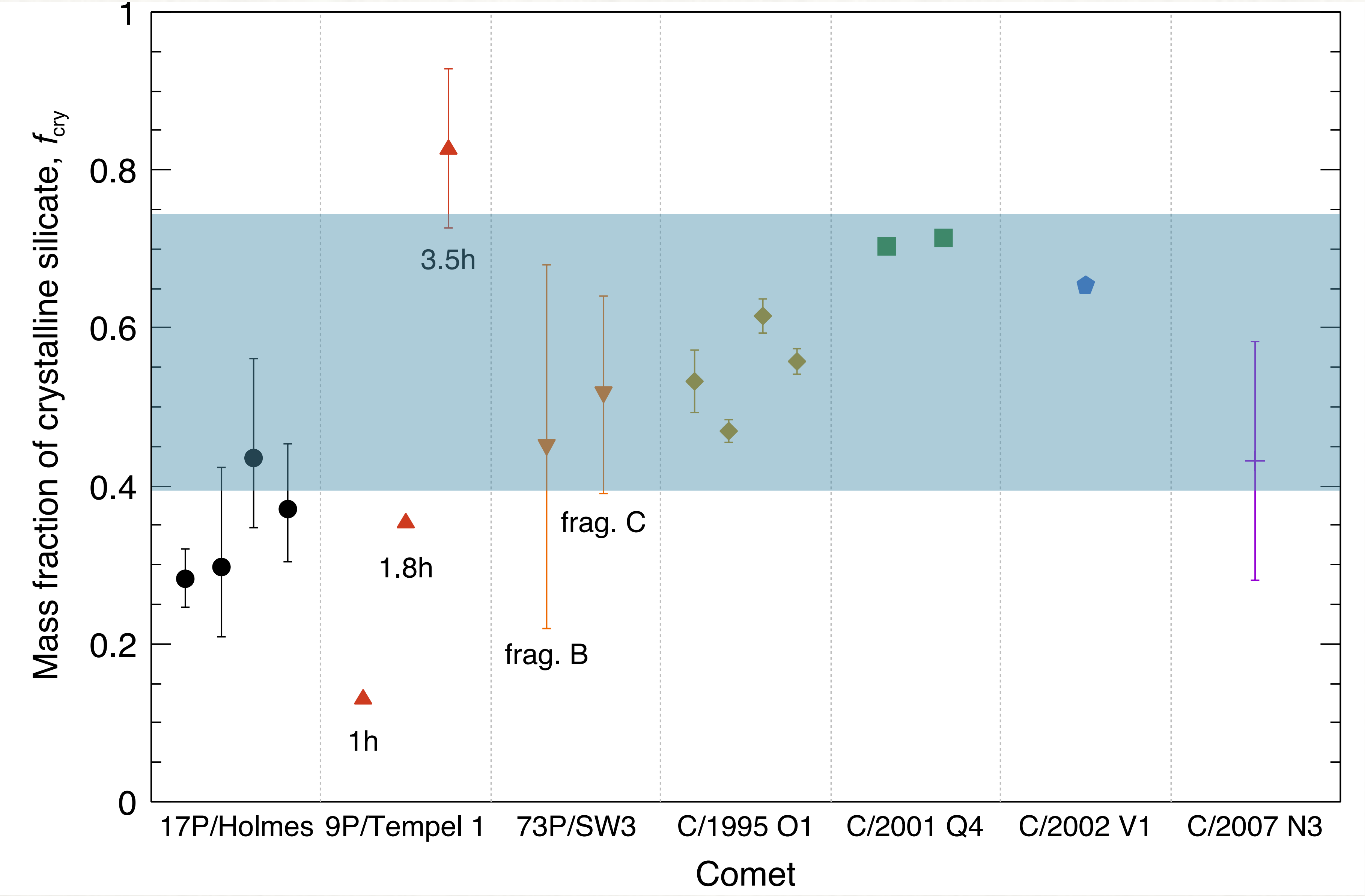
(Shinnaka+ 2018, AJ, 156, 242)

Crystalline fraction

(Shinnaka+ 2018, AJ, 156, 242)

Comet	UT Date	r_H (au)	D	a_p (μm)	N	f_{cry}	f_{OP}	ref
17P/Holmes	Weighted mean	2.45	—	—	—	0.31 ± 0.03	$1.20^{+0.16}/_{-0.12}$	
	2007 Oct 25	2.44	3.0	$0.10^{+0.01}/_{-0.00}$	$3.34^{+0.09}/_{-0.03}$	0.28 ± 0.04	$1.21^{+0.20}/_{-0.17}$	
	2007 Oct 26	2.45	3.0	$0.10^{+0.03/-}{}_{0.00}$	$3.07^{+0.14}/_{-0.03}$	$0.30^{+0.12}/_{-0.10}$	$1.73^{+0.75}/_{-0.53}$	
	2007 Oct 27	2.45	3.0	$0.10^{+0.12}/_{-0.00}$	$2.93^{+0.44}/_{-0.03}$	$0.44^{+0.13}/_{-0.09}$	$0.93^{+0.29}/_{-0.21}$	
	2007 Oct 28	2.45	3.0	$0.10^{+0.14}/_{-0.00}$	$3.00^{+0.18}/_{-0.02}$	$0.37^{+0.08}/_{-0.07}$	$1.95^{+0.63}/_{-0.47}$	
9P/Tempel 1	2005 Jul 4 (+1.0 h)	1.51	2.857	0.3	3.7	0.13 [*1]	0.92 [*3]	[1]
	2005 Jul 4 (+1.8 h)	1.51	2.857	0.5	3.7	0.36 [*1]	7.22 [*3]	[1]
	2005 Jul 4 (+3.5 h)	1.51	2.857	0.4	3.6	0.83 ± 0.10	6.5 ± 1.9	[2]
73P-B/SW3	2006 Apr 29	1.11	2.727	0.5	3.4	0.45 ± 0.21	0.25 ± 0.16	[3]
73P-C/SW3	2006 Apr 30	1.09	2.727	0.3	3.4	0.52 ± 0.13	>17	[3]
C/1995 O1	1996 Oct 11–14	2.8	2.8	0.2	3.4	0.53 ± 0.04	2.65 ± 0.51	[4]
	1997 Feb 14–15	1.21	2.5	0.2	3.7	0.47 ± 0.01	1.55 ± 0.07	[4]
	1997 Apr 11	0.97	2.5	0.2	3.7	0.62 ± 0.02	2.26 ± 0.17	[4]
	1997 Jun 24–25	1.7	2.727	0.2	3.7	0.56 ± 0.04	1.57 ± 0.08	[4]
C/2001 Q4	2004 May 11	0.97	3.0	0.3	3.7	0.70 [*3]	3.57 [*3]	[5]
	2004 Jun 4	1.02	3.0	0.2	3.6	0.71 [*3]	6.88 [*3]	[6]
C/2002 V1	2003 Jan 10	1.18	2.857	0.5	3.5	0.66 [*3]	2.63 [*3]	[6]
C/2007 N3	2009 Mar 3	1.45	2.727	0.9	4.2	0.43 ± 0.15	0.35 ± 0.11	[7]

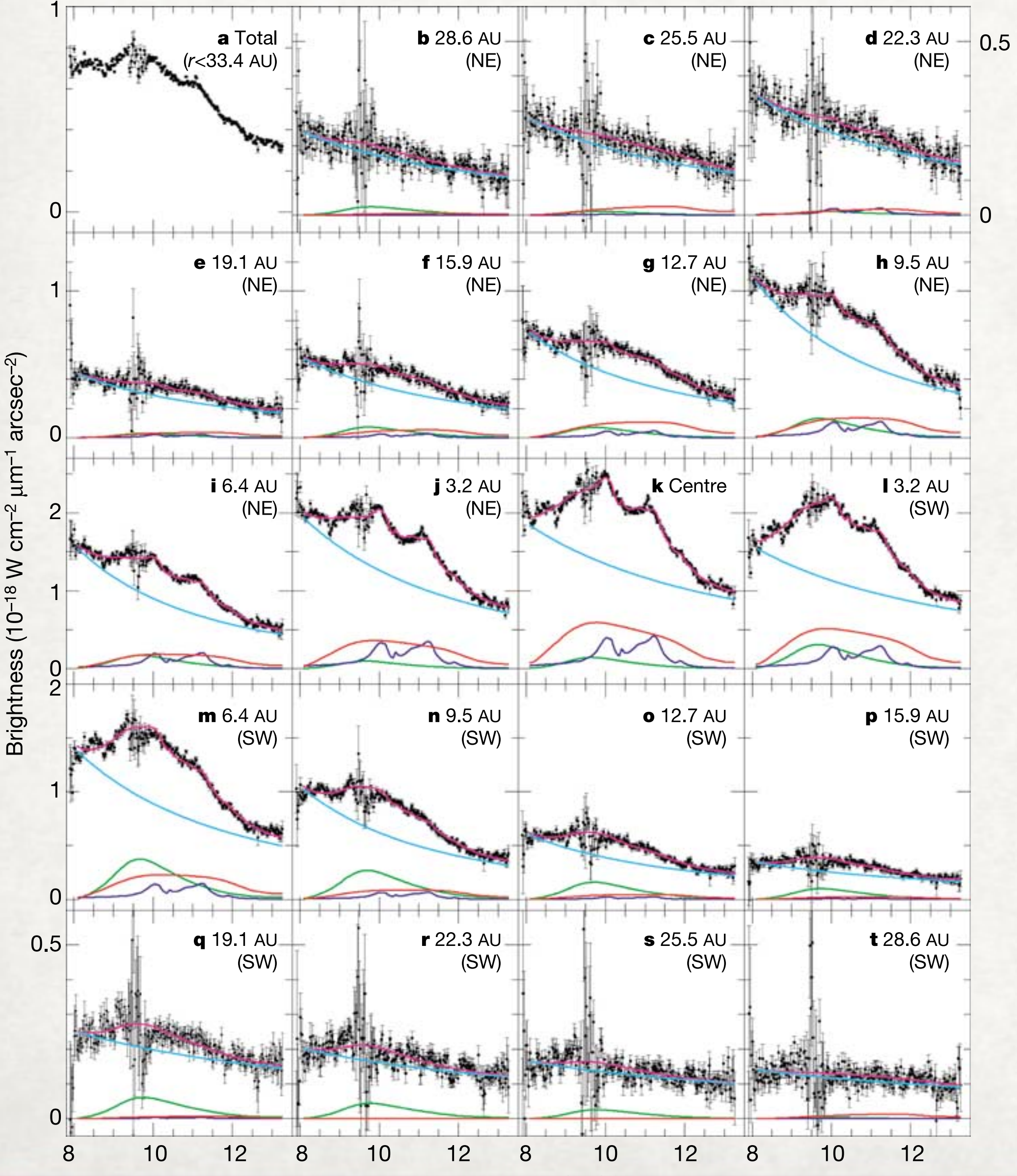
Crystalline fraction

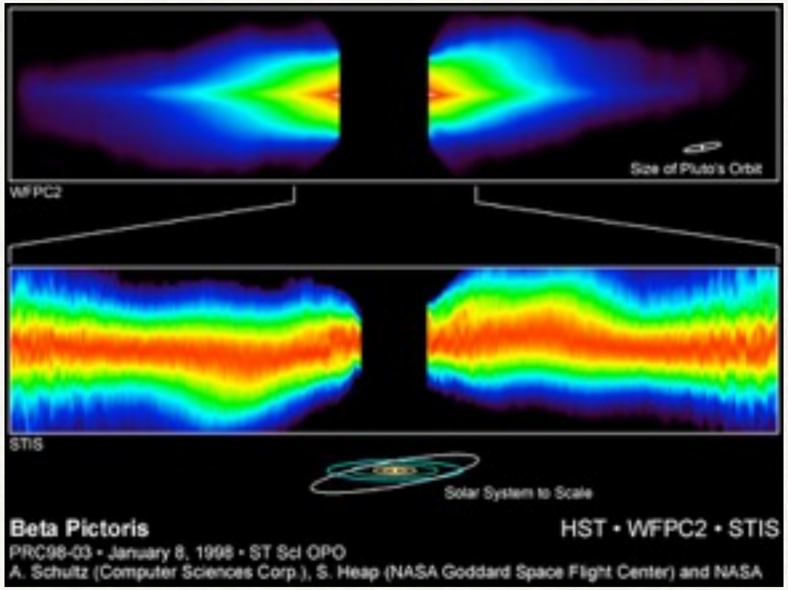


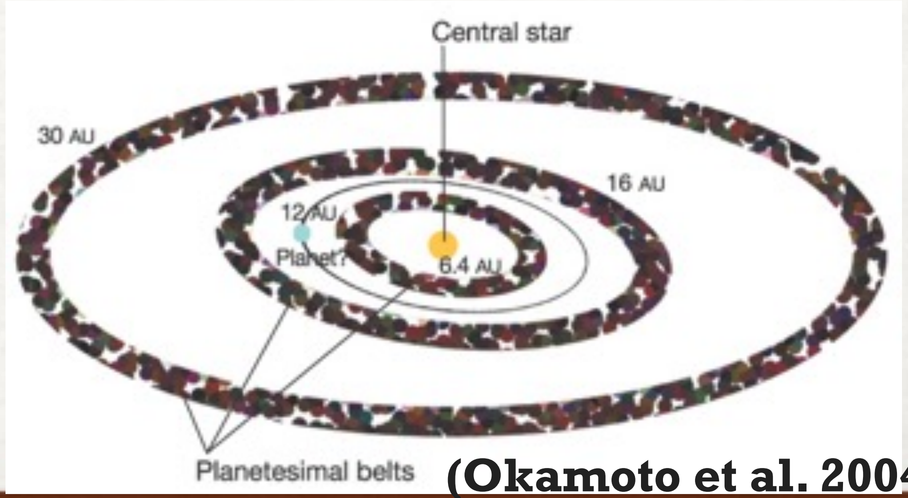
Silicate grains in debris disks

β Pictoris - young (10--20 Myr), Main sequence star (A6V)

Debris disk (Exo-Zodi?) - dust rings?





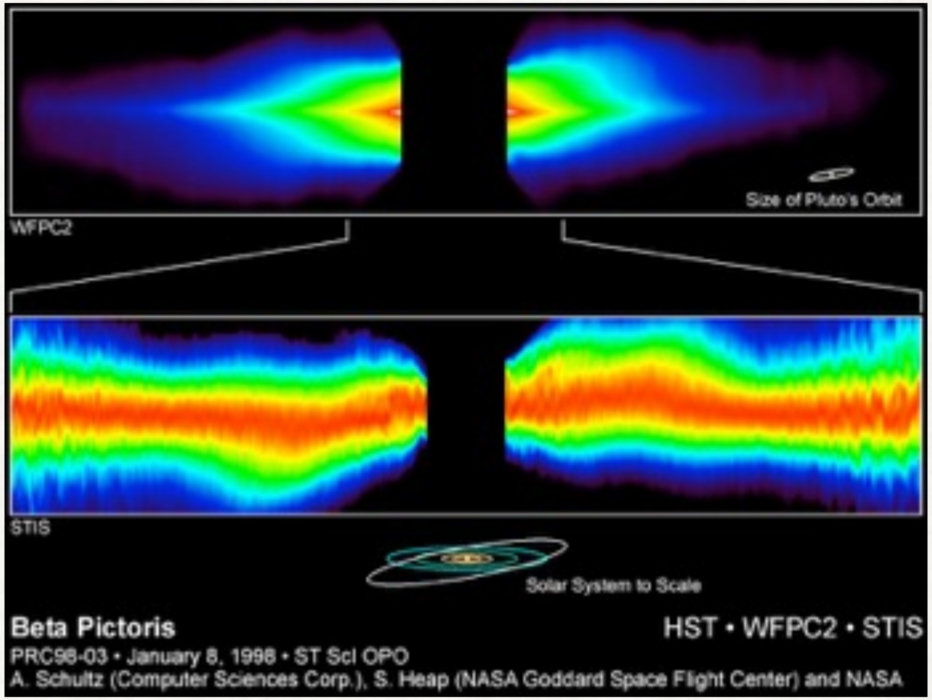


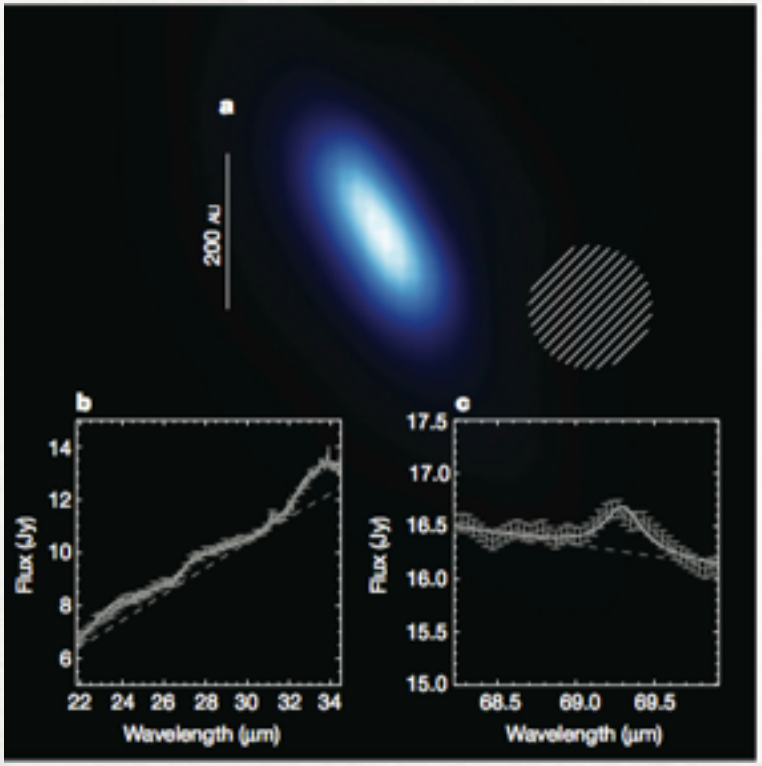
(Okamoto et al. 2004)

Zodi and Exo-Zodi

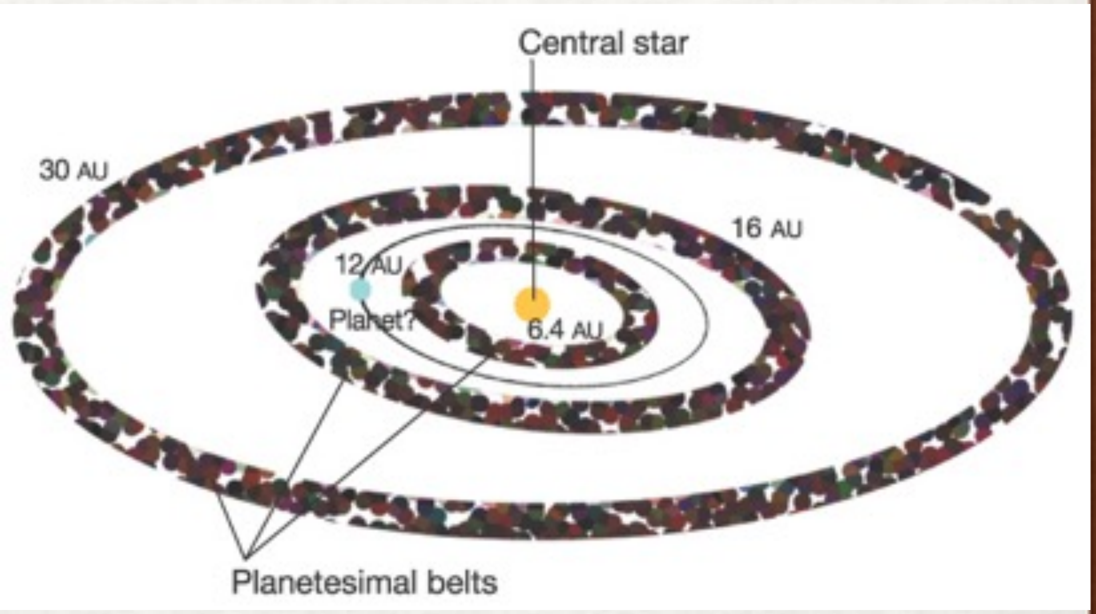
β Pictoris

- young (10--20 Myr)
- Main sequence star (A6V)
- Debris disk (Exo-Zodi?)
  - 33, 69 μm silicate feature
  - comet-like dust grains?





(de Vries et al. 2012)

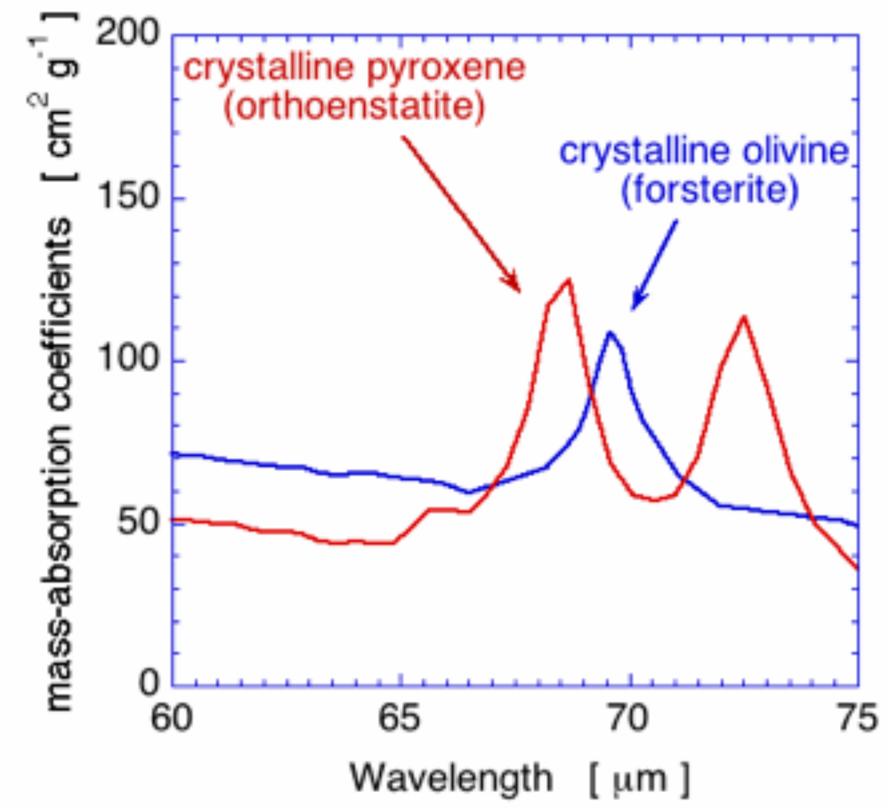


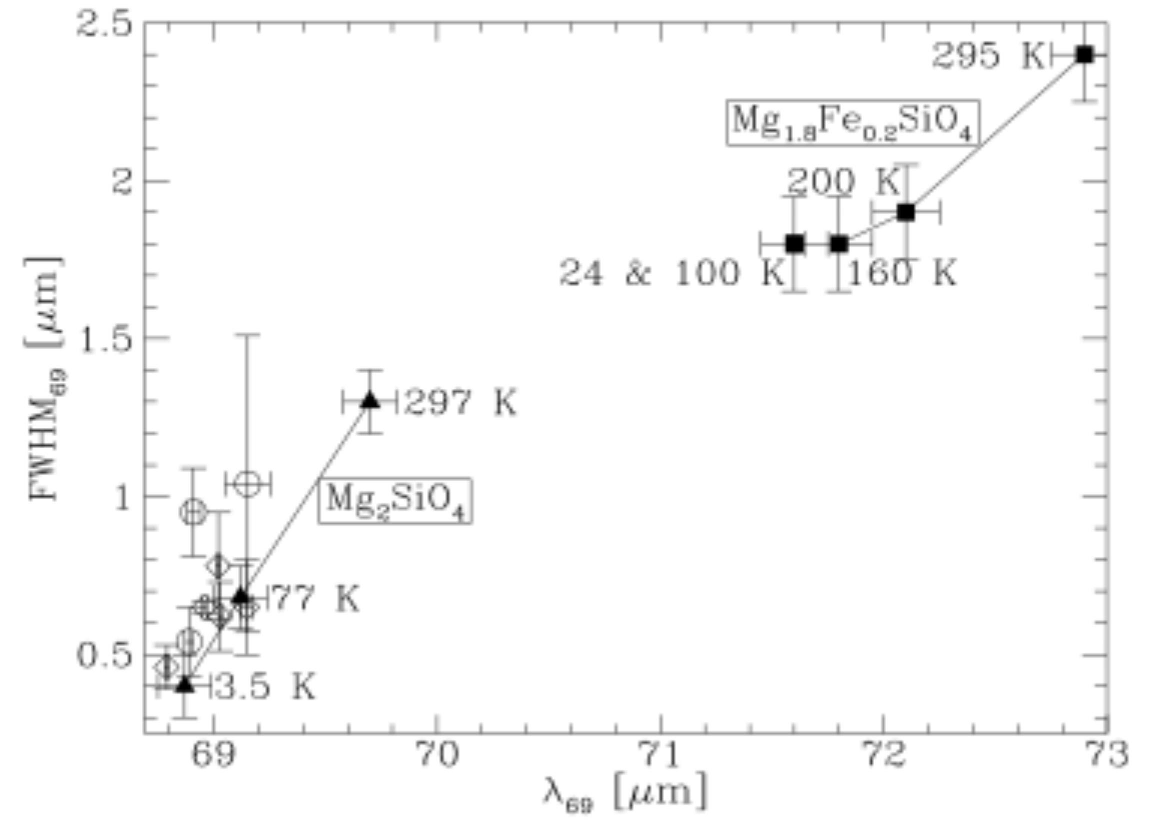
(Okamoto et al. 2004)

69 µm silicate feature

★ 69μm feature --> 遠赤外線分光観測

-- 彗星ではまだ明確な観測成功例無し（？）





ピーク波長・FWHMが結晶質

ダストの組成・温度に敏感

Future space missions in IR after AKARI

- JWST (202x --) NIR+MIR
  - NIRcam, NIRspec: 0.6--5 μm
  - MIRI: 5-28 μm

- SPICA (late 2020s --) MIR+FIR
  - SMI: 12-36 μm (Higr-res at 12-18 μm)
    - CO_2 15μm, silicate features
    - 20, 30 μm band silicate features
  - SAFARI: 34-230 μm

We don't have CO_2 observations for more than 10 years after AKARI

Summary for cometary ice and dust

- ✴ 彗星の氷は H_2O, CO_2, CO rich (CO強度が強い彗星で CO/CO_2 ~ 1.0)
- ✴ 多くの彗星で、結晶質ケイ酸塩のフィーチャも受かっている

  結晶質比率は、fcry ~ 0.3−0.7
- ✴ CO/CO_2 , ダストの結晶質率は、彗星の type (OCs, JFCs) による大きな違いは見られない
- ✴ 原始太陽系円盤中での彗星核の形成場所は、まだ不定性が大きいが、ざっくり 5—35 au？
- ✴ 彗星の値は、太陽 (G2V) 系の5-35 au 付近の結果

- ✴ デブリ円盤の CO と結晶質ケイ酸塩は、太陽系の comet-like な起源（より内側で形成されて外縁部に運ばれた）なのか？

  clasical KBO-like な遠方形成微惑星起源の可能性は？