Mid-infrared Observations of Comets with Subaru Telescope

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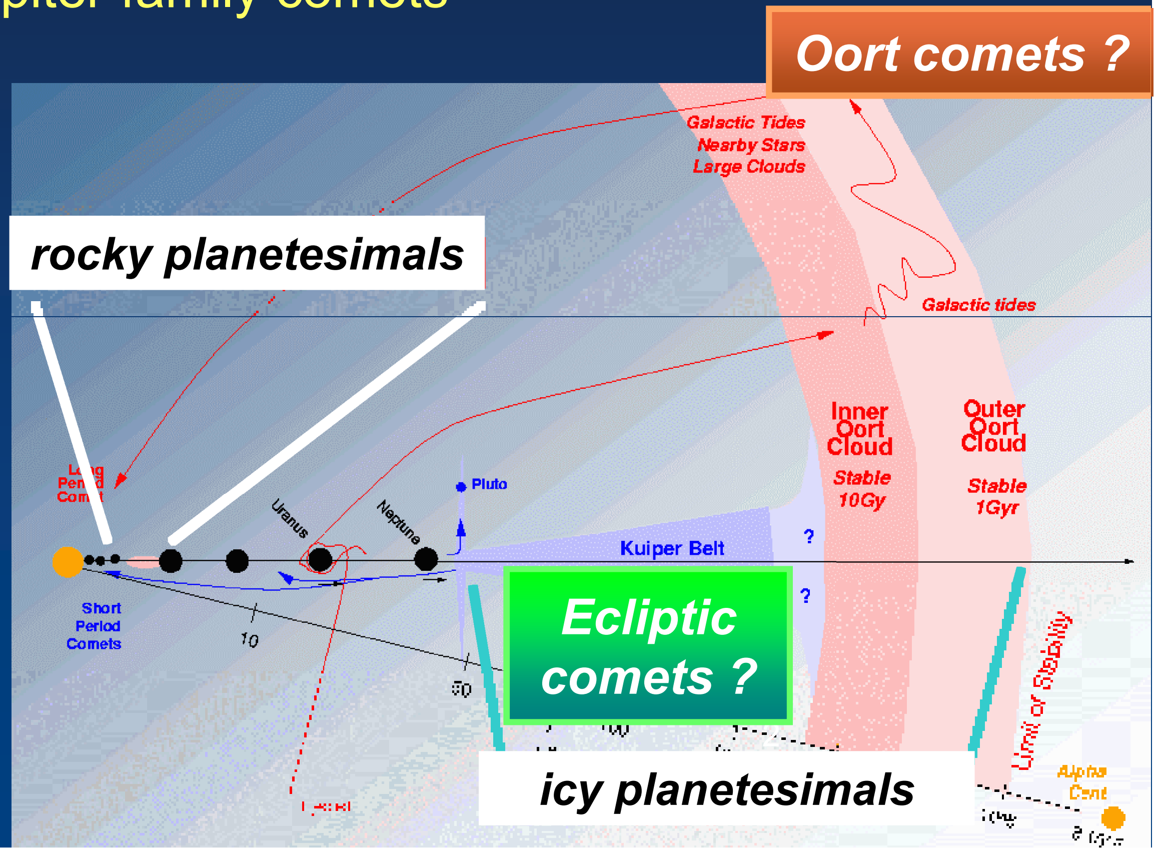
Introduction

- **Comets - dirty water ice = ice (volatile) + dust (refractory)**
  - frozen reservoirs of the early solar nebula (cold region)
  - Two dynamical types of comets: **Oort-cloud comets (OCs)** and **Ecliptic comets (ECs)** different heliocentric distances of their birth places
- **Spectroscopic data of a large number of comets**
  - enable us to characterize the property of cometary grains
  - difference between Oort cloud & Jupiter family comets
- **Understanding how primitive grains were formed or processed in the early solar nebula**
  - a clue to understand the origin and evolution of the solar system
  - formation process of planetesimals from dust grains



Introduction

Crystalline silicate features have been found in mid-IR spectra of (Oort) comets(hot condensates T >~ 800K)

anealing of amorphous silicate at the inner region of the early solar nebula ?

a diffusive transportation toward the outer region where comets were born ?

To verify whether a diffusive transportation was effective or not

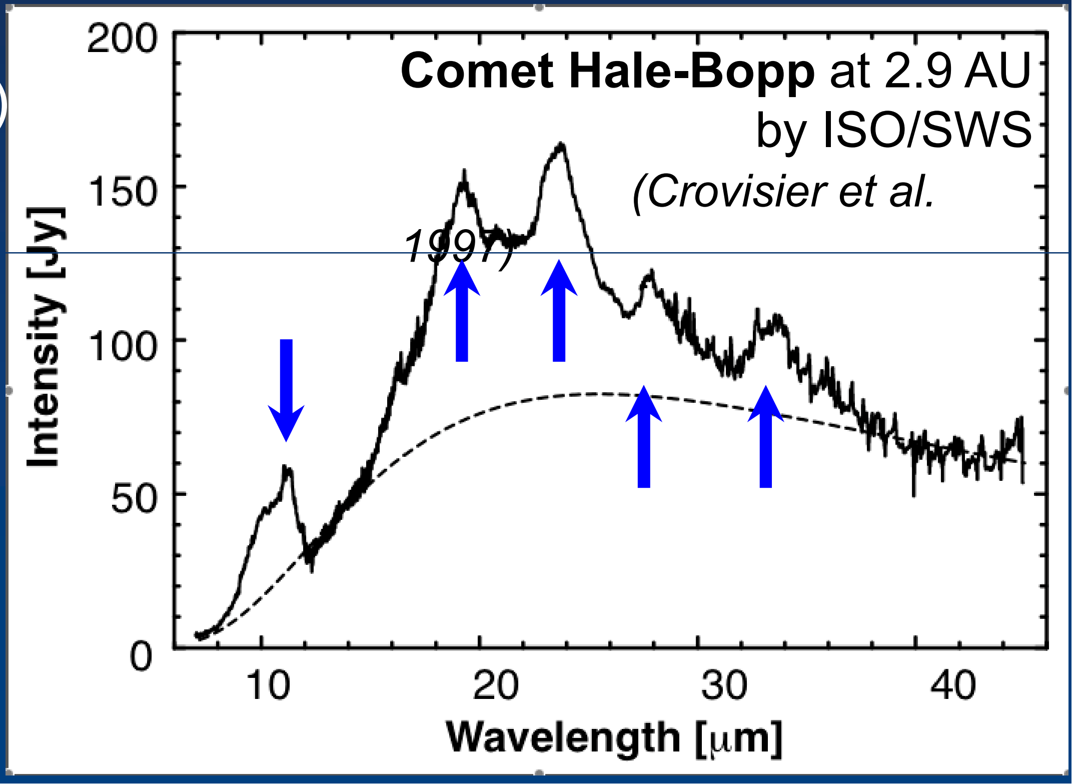
a quantitative study of crystalline silicate in comets is crucial.

high quality mid-IR data with a moderate spectral resolution (R > 100)

high sensitivity at mid-IR (not only brightest comets such as Hale-Bopp)

different between Oort cloud & Ecliptic comets ?

No clear crystalline feature detection for ECs before Subaru



Observations

- Subaru＋COMICS (8-13 μm; R～250)

mid-IR low-resolution spectroscopy

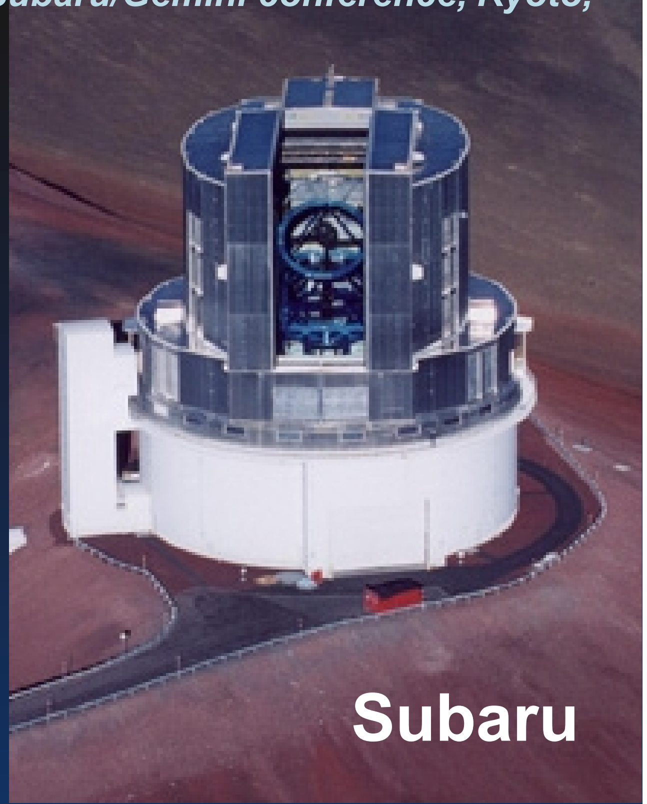
a powerful tool for the study of dust mineralogy

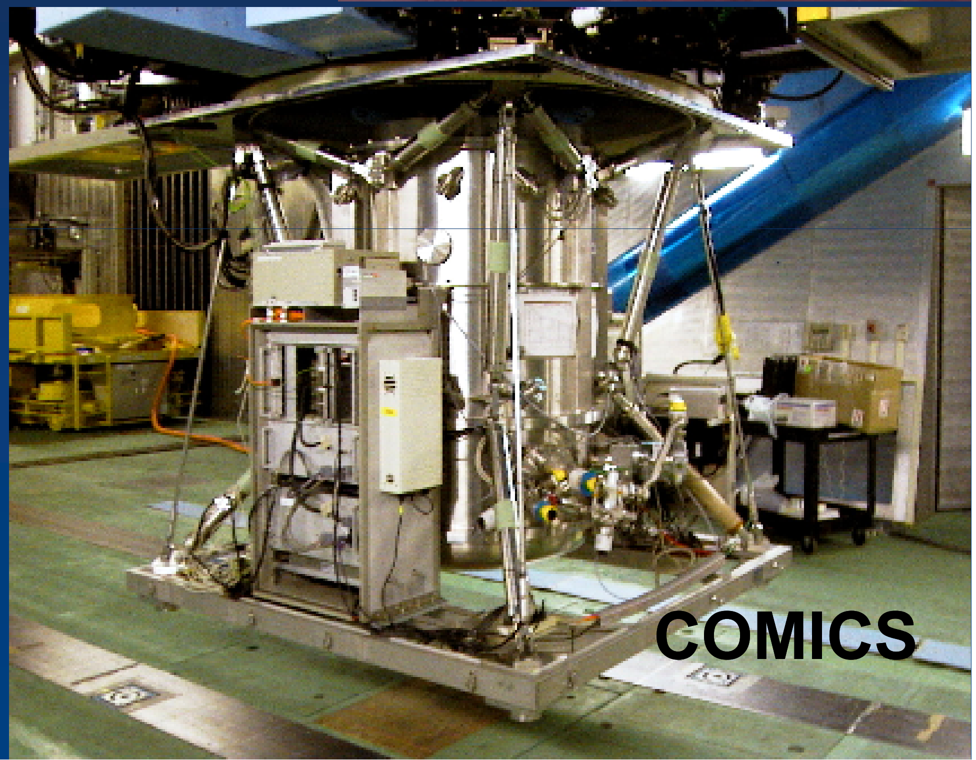
Oort cloud comets

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

Ecliptic comets

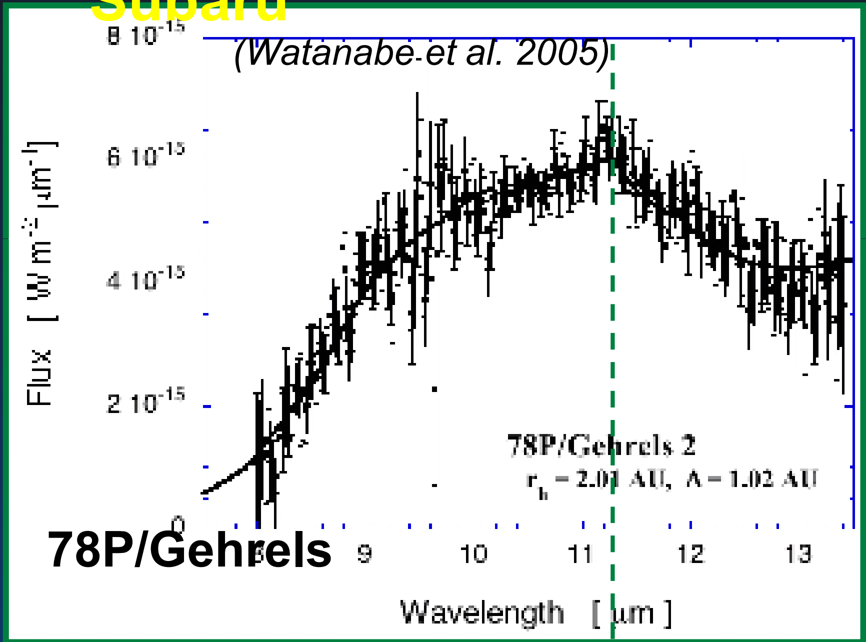
2P/Encke, 78P/Gehrels
9P/Tempel → Deep Impact
21P/Giacobini-Zinner
73P/Schwassmann-Wachmann
4P/Faye, 17P/Holmes, 8P/Tuttle

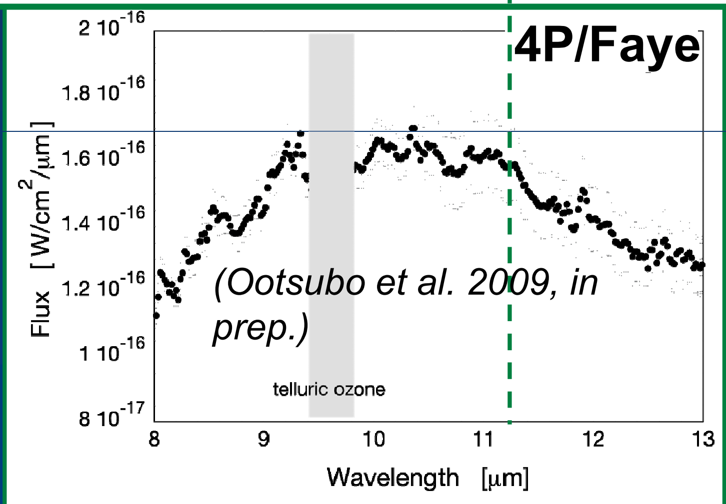


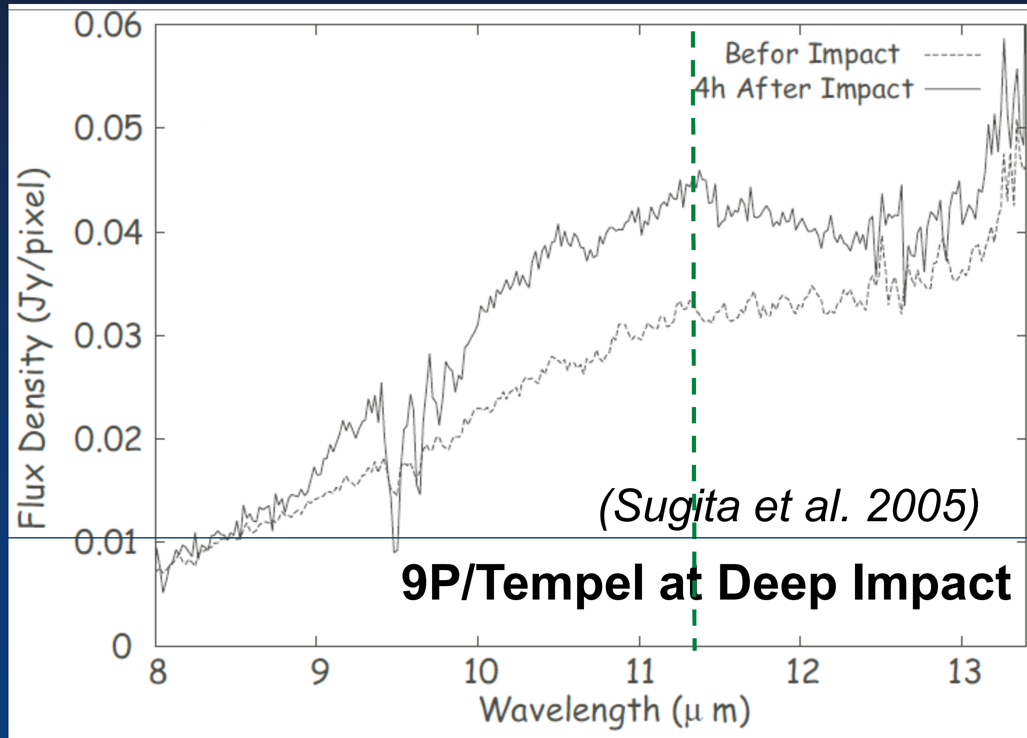


Result (1)

No clear crystalline feature has been reported for ECs before Subaru



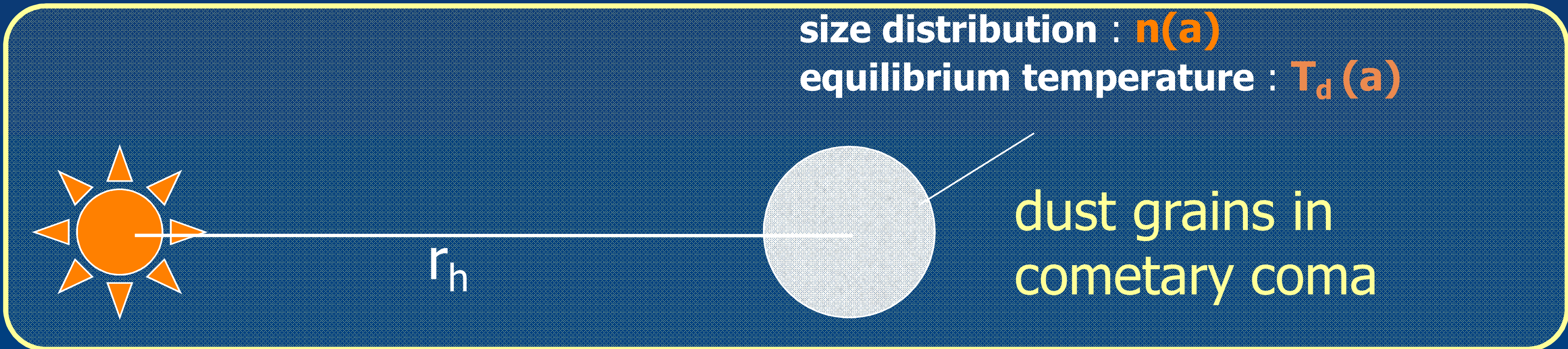




We detected crystalline silicate feature in EC spectra !

Thermal emission model of comet

- **Modeling of Thermal IR emission from grains in the coma**
  (cf. Harker et al. 2002, Ootsubo et al. 2007)
  - **the comet coma is optically thin**
  - **all the grains are at the same heliocentric distance r_h**
  - **equilibrium temperature T_d for each grain (set by the balance between solar radiation)**
  - **the comet SED is the sum of each grain's IR spectrum**
    - **size distribution, population of 5 mineral species**



Thermal emission model

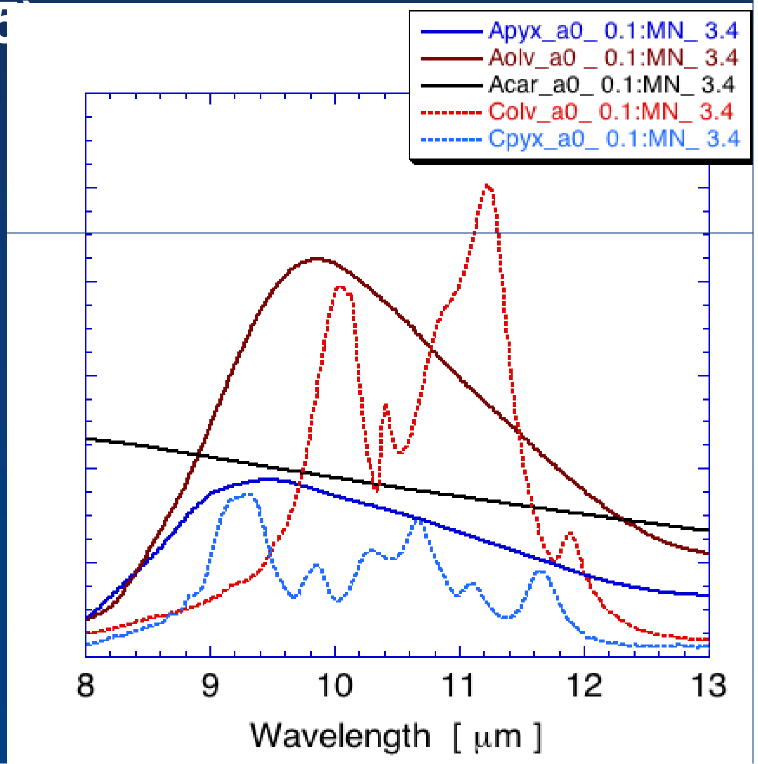
- Homogeneous spherical Mie grains: Q_{em} (= Q_{abs})
  dust grains of 5 distinct and separate mineral species
  (optical constants in UV-FIR region are available)
  Effective Medium Theory (Maxwell-Garnet theory) is used for the modeling of the fractal porous dust grains (vacuum inclusion)

■ amorphous :

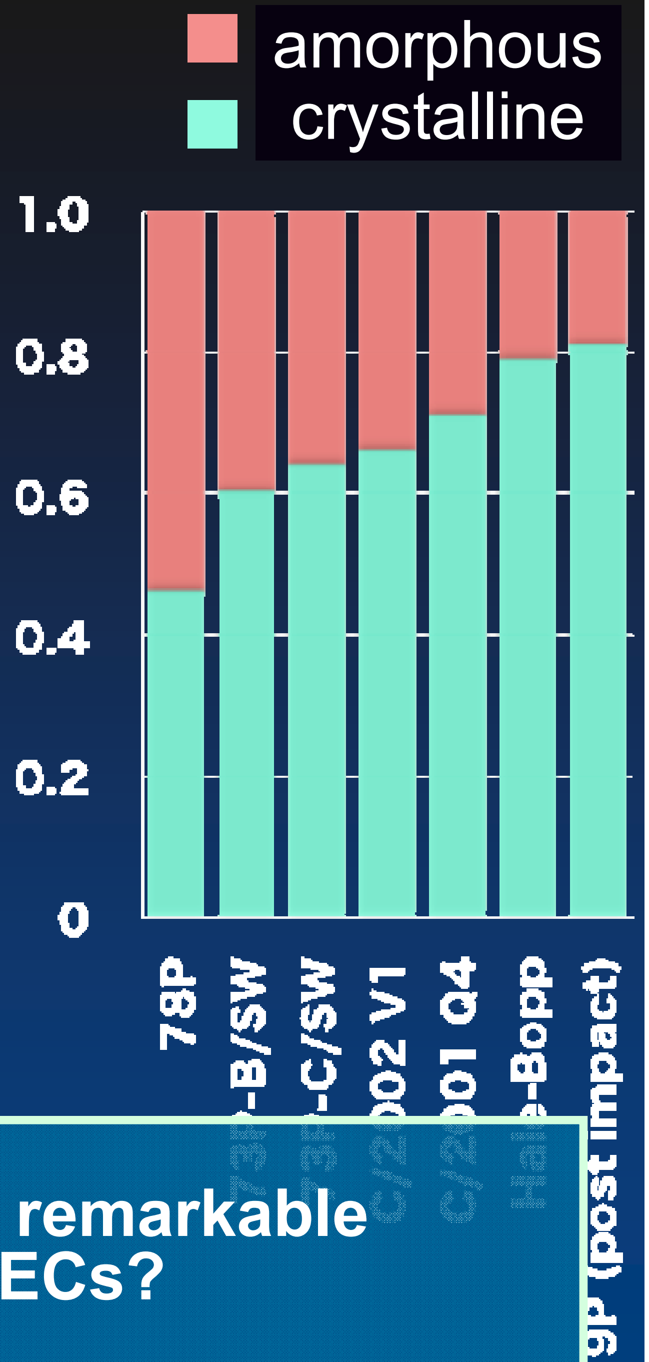
1. amorphous carbon (optical constants from Edoh 1983)
2. amorphous olivine (Dorschner et al. 1995)
3. amorphous pyroxene (Dorschner et al. 1995)

■ crystalline :

4. crystalline olivine (forsterite)
   (Fabian et al. 2001 for T_d,
   Koike et al. 2003 for feature)
5. crystalline pyroxene (orthoenstatite)
   (Jäger et al. 1998 for T_d,
   Chihara et al.2002 for feature)



	r_h [AU]	N	a_{peak} [μm]	D	f_crystal (%)
Q4 NEAT	1.02	3.6	0.2	3.0	71
	0.97	3.7	0.3	3.0	70
V1 NEAT	1.18	3.5	0.5	2.8	66
	1.15	3.7	0.5	3.0	69
Hale-Bopp	0.97	3.7	0.2	2.5	79
	1.21	3.7	0.2	2.5	68
9P/Tempel (post-impact)	1.51	3.9	0.8	2.8	78-84
73P-B/SW3 (fragmentation)	1.06	3.5	0.3	2.8	58-63
73P-C/SW3 (fragmentation)		3.5	0.4	2.72	62-65
17P/Holmes (burst)	2.44	-	-	-	-
78P Gehrels	2.01	3.6	0.6	3.0	46
2P/Encke		-	-	-	-
4P/Faye	1.72	-	-	-	-
8P/Tuttle	1.23	-	-	-	-



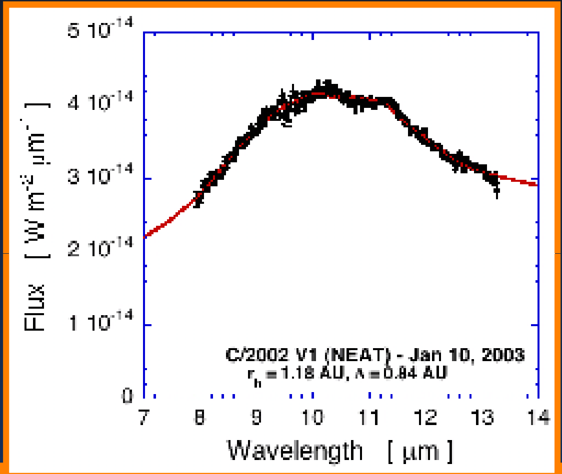
Oort comets vs **Ecliptic comets**

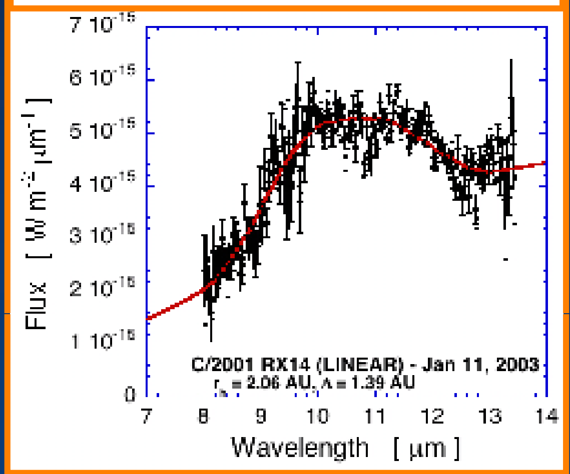
difference of mineralogy is not so remarkable
grain evolution on the nucleus of ECs?

--> on-going continuous observational program

Result (2)

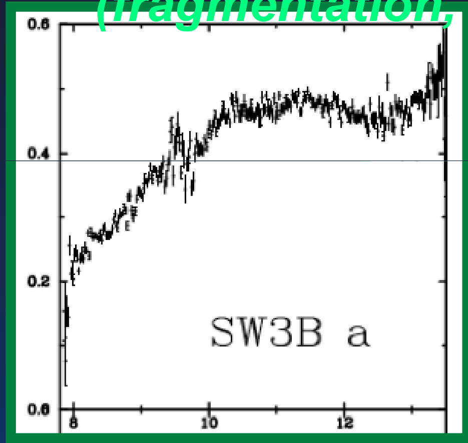
Oort cloud comets

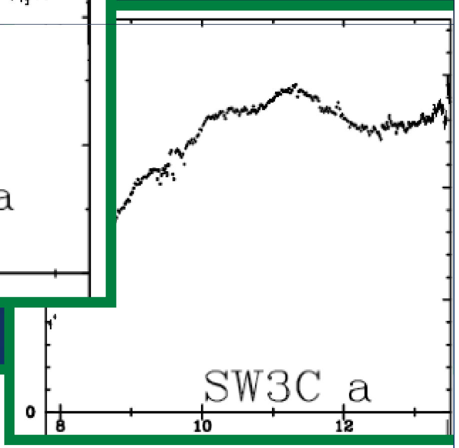


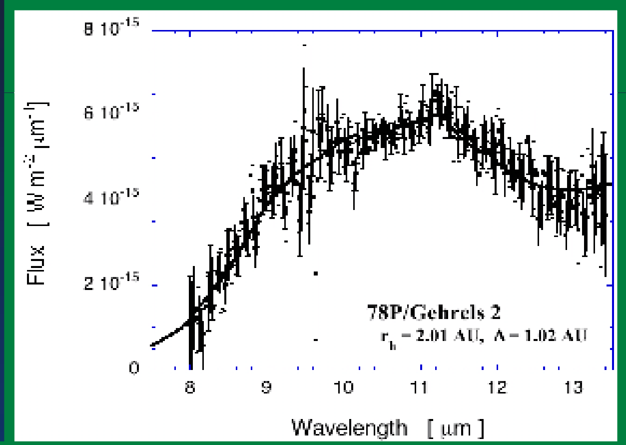


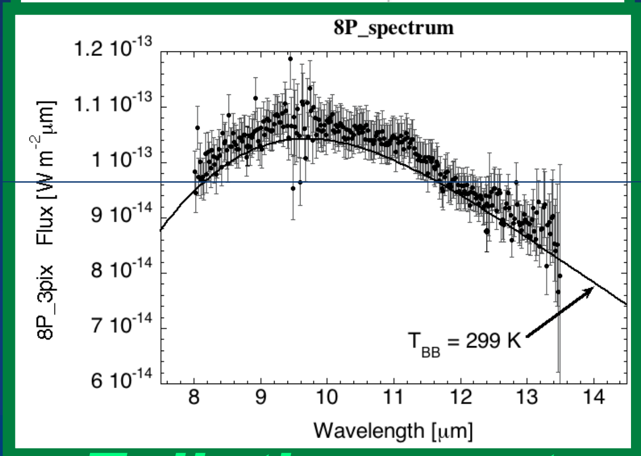
active Ecliptic comets

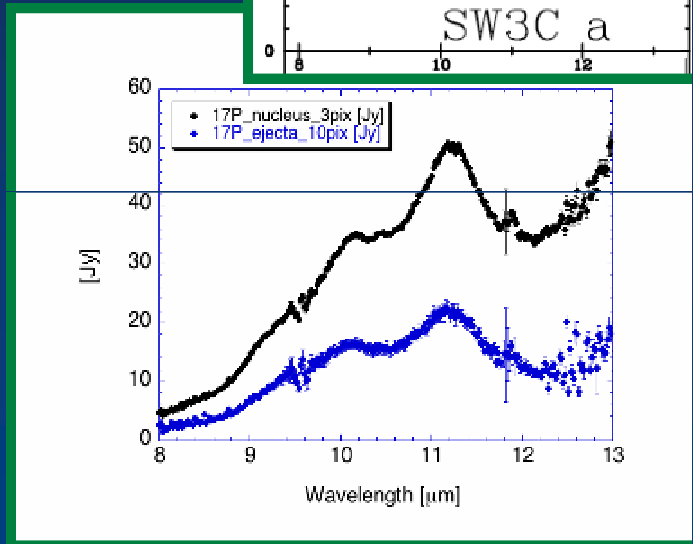
(fragmentation, burst, etc...)











Ecliptic comets

crystalline-to-amorphous silicate ratio
silicate feature strength

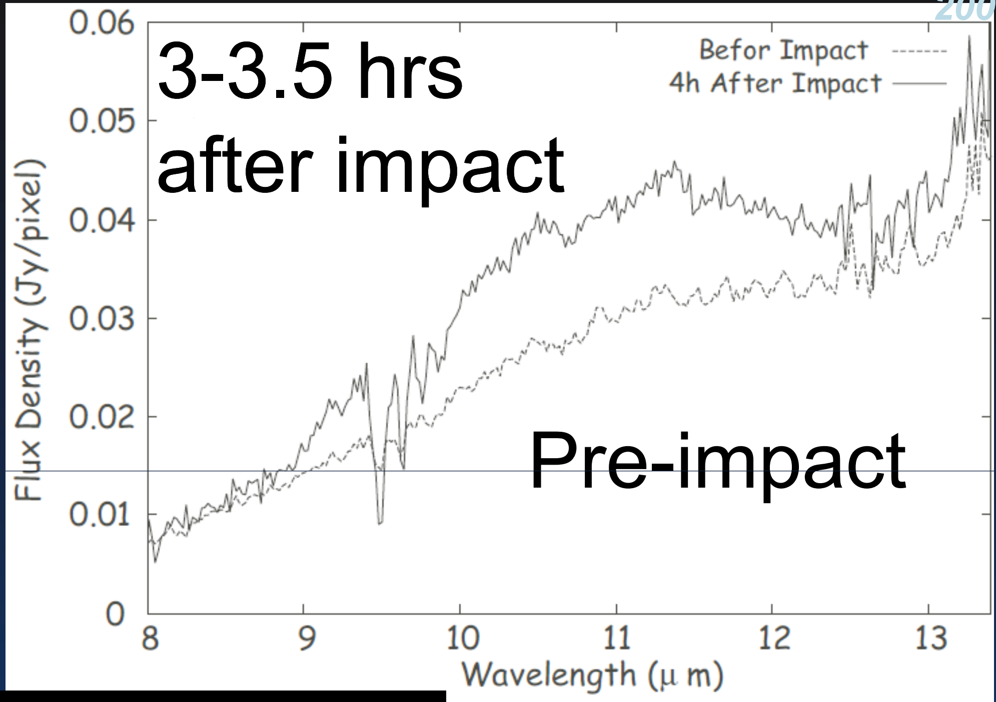
vs

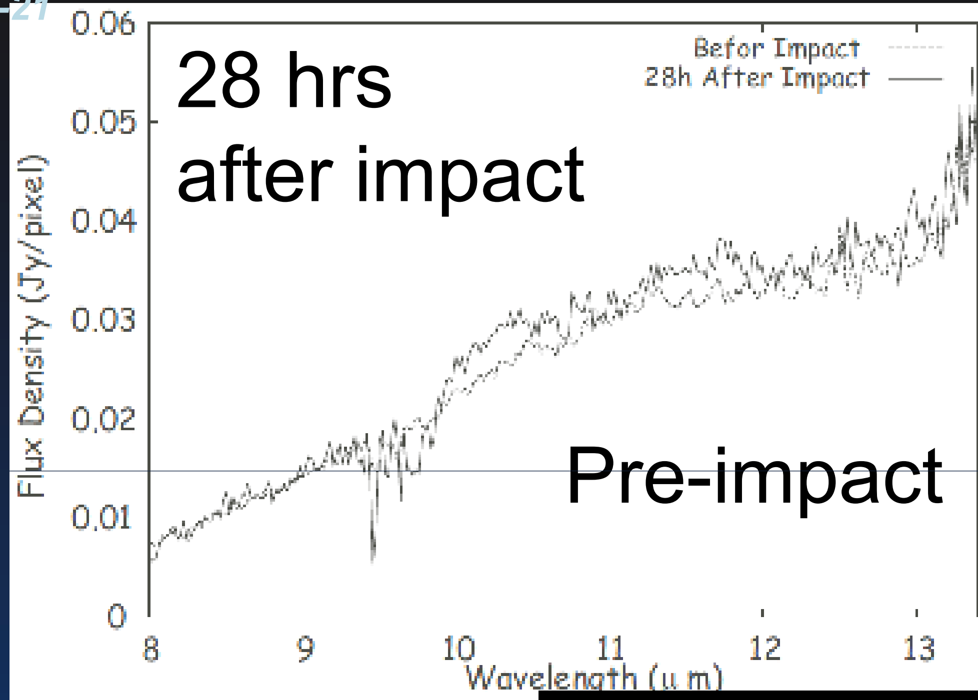
orbital parameters
(birth place?)

- Mid-infrared spectroscopy
  - powerful tool for the study of dust mineralogy

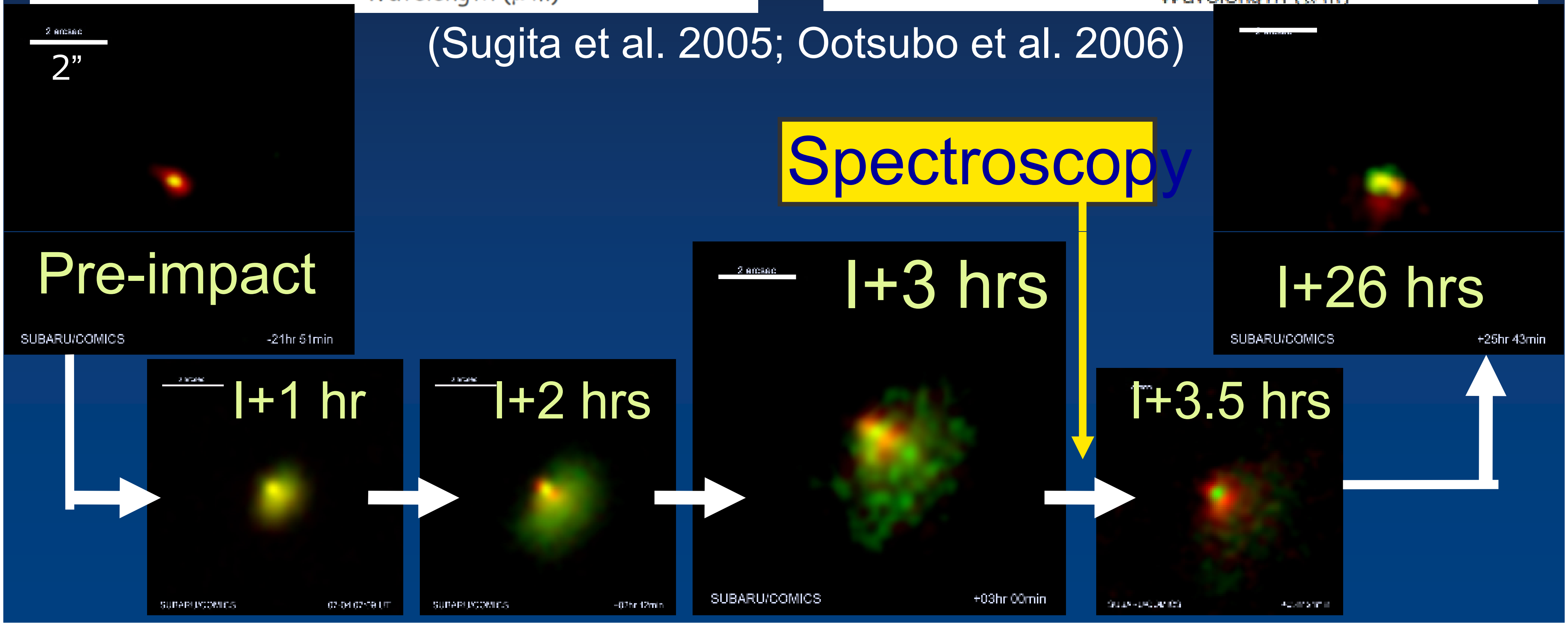
- Space telescopes, such as Spitzer Space Telescope (dried up last week!), can observe with broader wavelength range and higher sensitivity than Subaru and Geimini in mid-IR

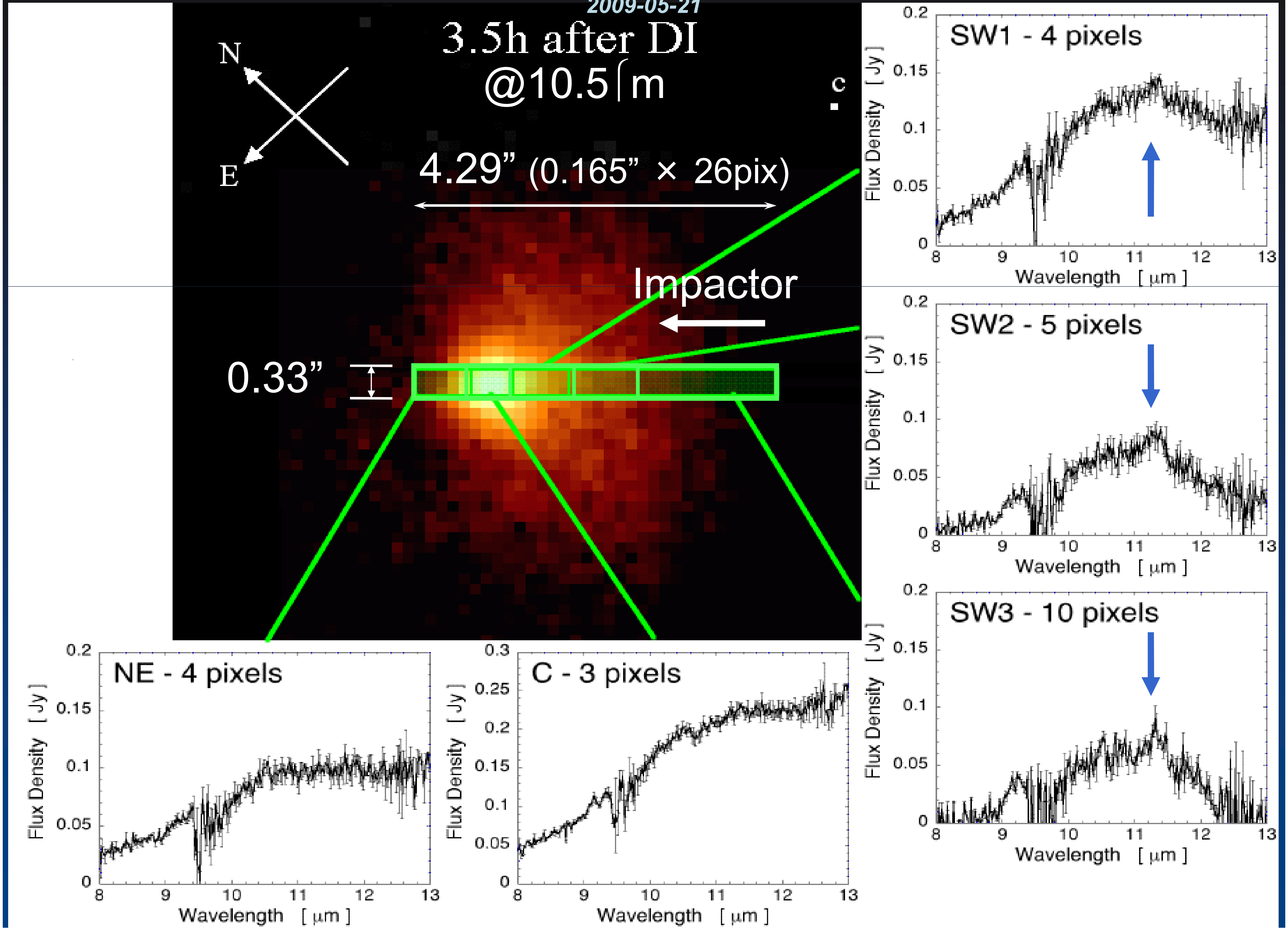
- **Spatial resolution achieved by the 8-m telescope of Subaru (and Gemini) surpasses that of space telescopes**
  - highly spatially resolved imaging and spectroscopy
  - (in) homogeneity of a comet nucleus in dust mineralogy
  - time evolution of the coma dust in the vicinity of the nucleus



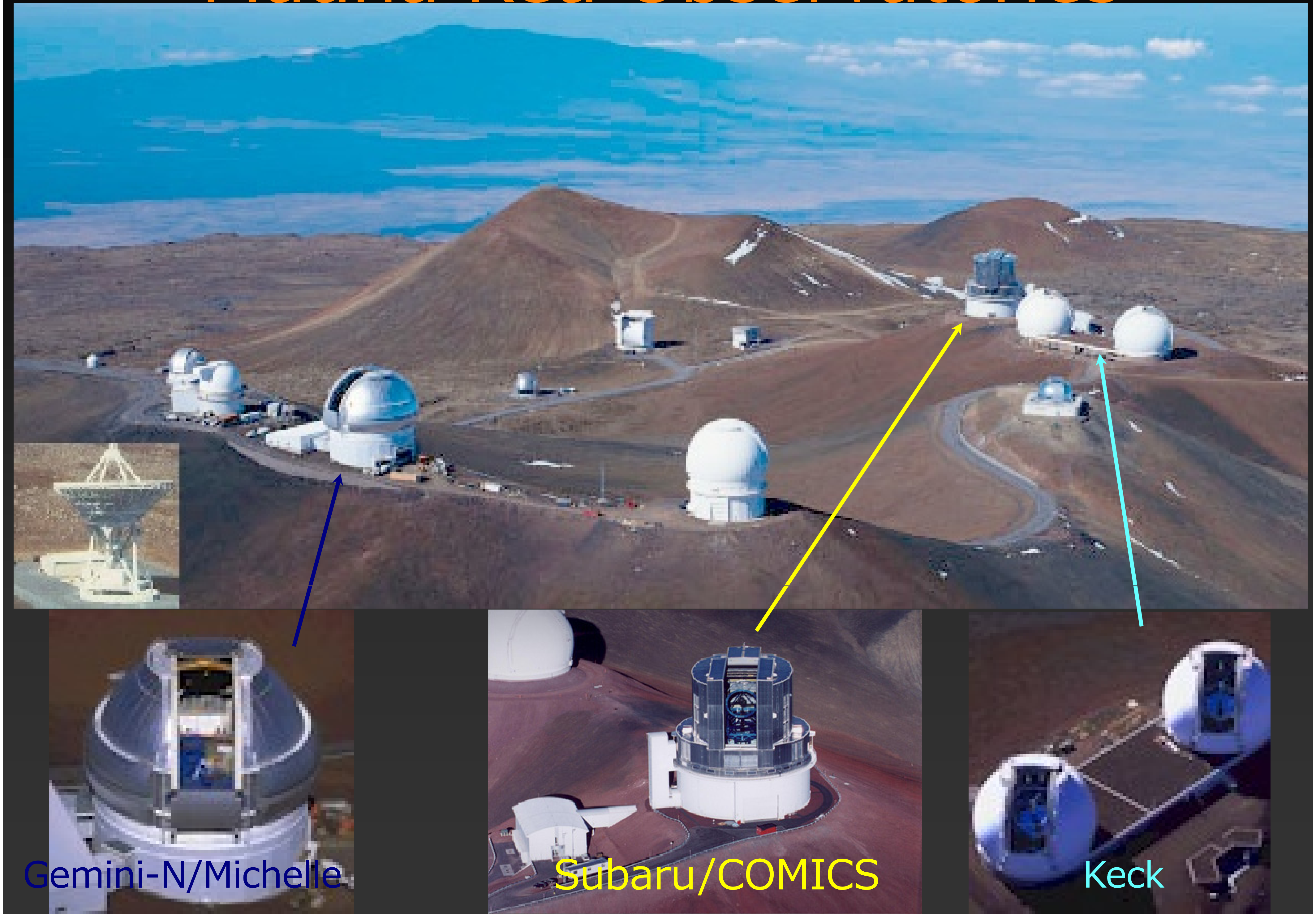


(Sugita et al. 2005; Ootsubo et al. 2006)

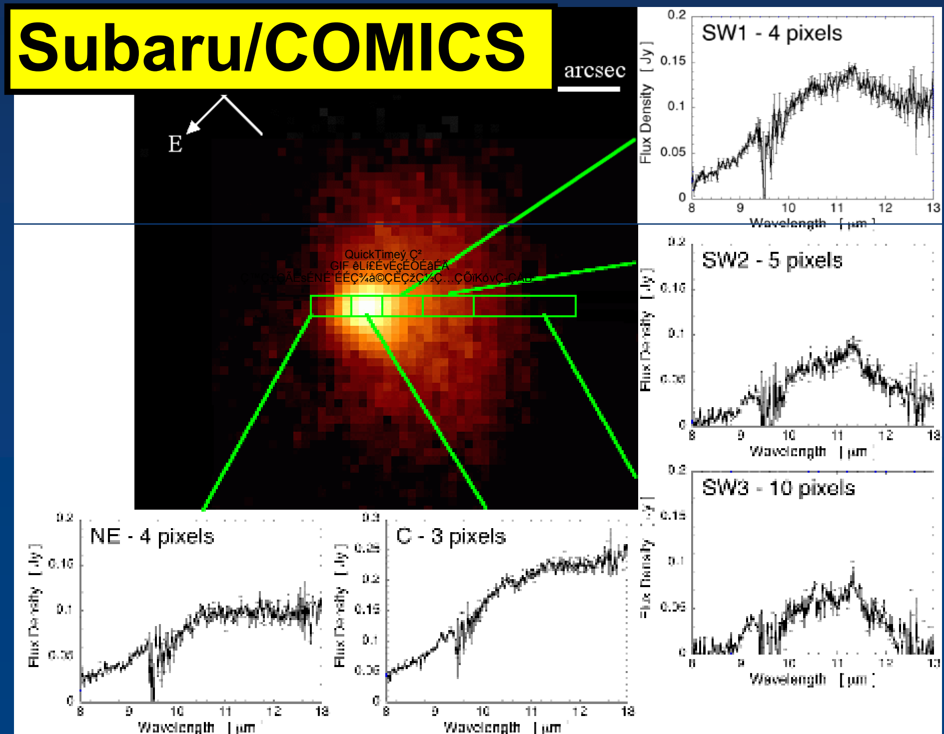


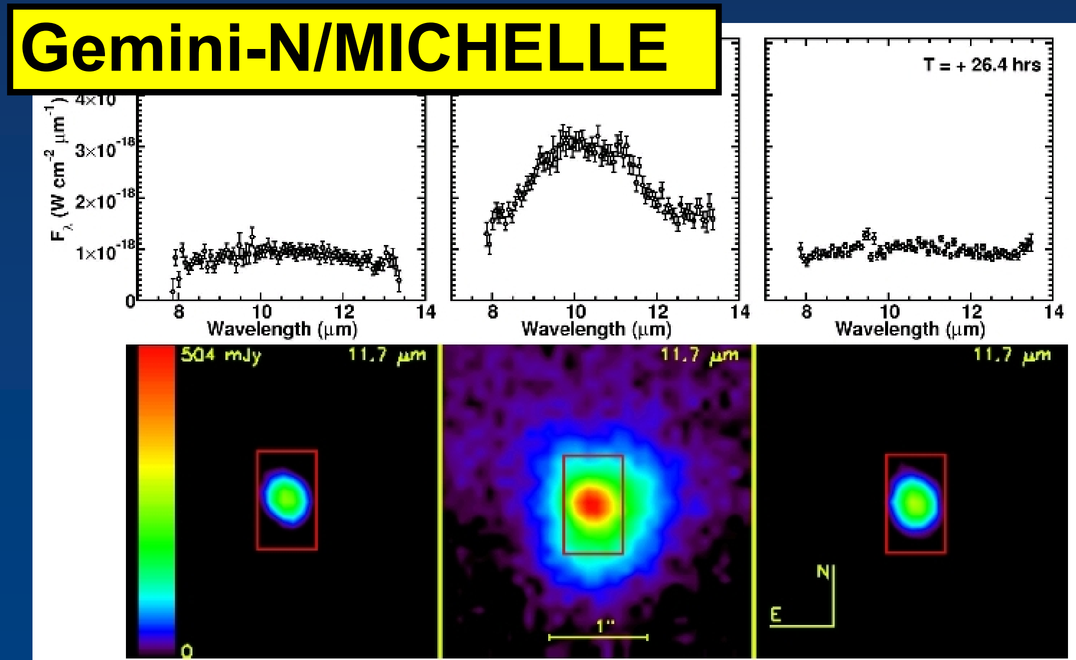

3.5h after DI
@10.5⌠m
N
E
c
4.29” (0.165” × 26pix)
Impactor
0.33”
SW1 - 4 pixels
SW2 - 5 pixels
SW3 - 10 pixels
NE - 4 pixels
C - 3 pixels
Flux Density [Jy]
Wavelength [μm]

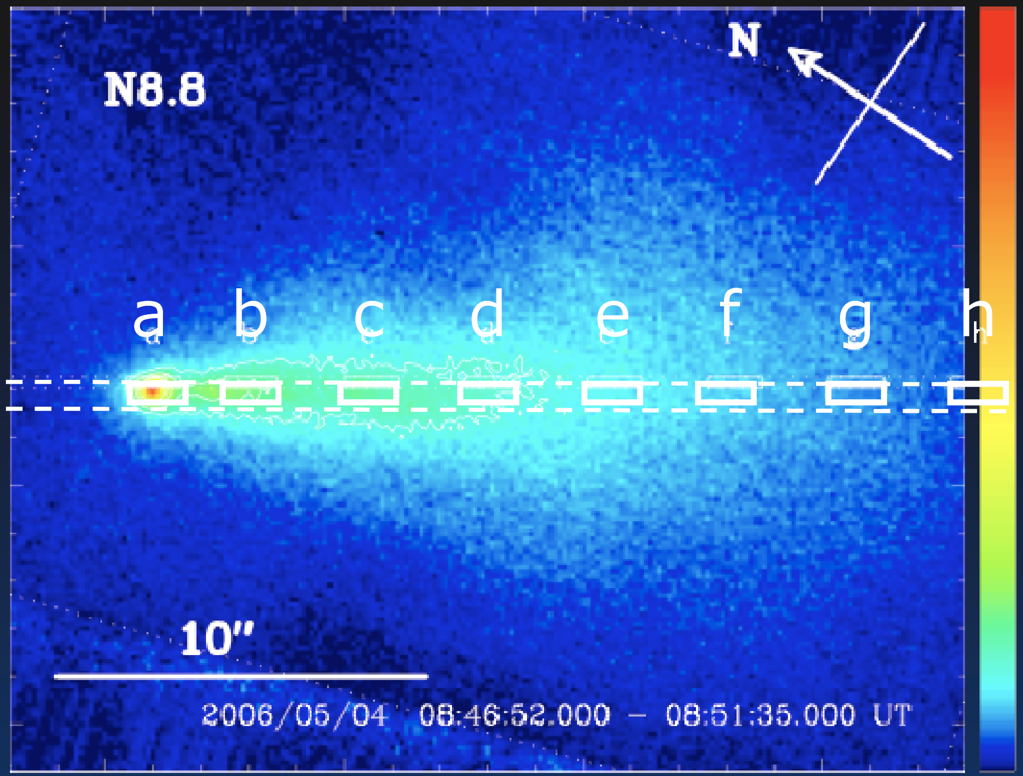
Mauna Kea Observatories

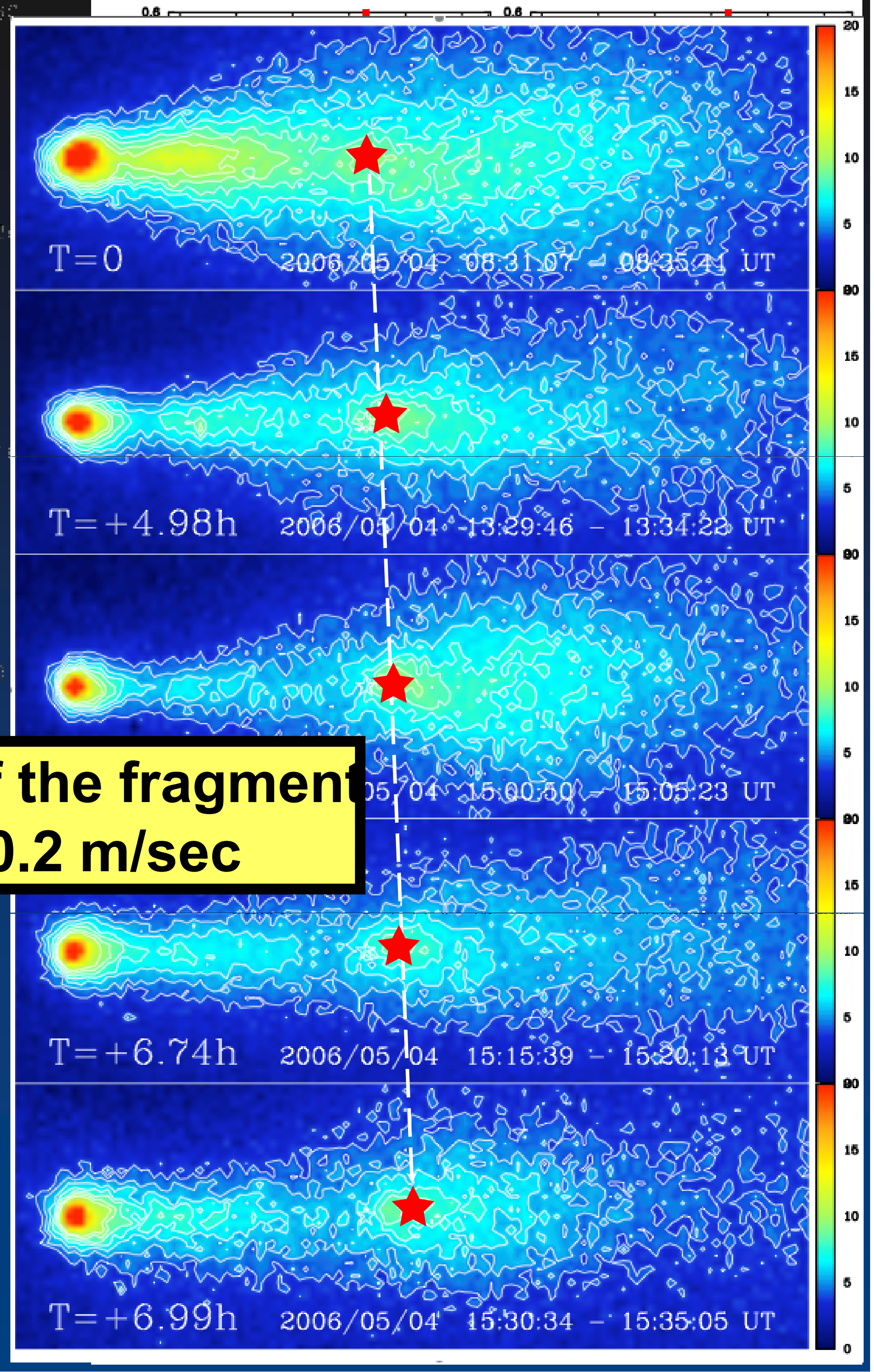


• Coordination with other Mauna-Kea telescopes









motion of the fragment
7 ± 0.2 m/sec

73P/SW - B

(2006/05/04UT)

rh = 1.06 AU, Δ = 0.11 AU

11.2 μm crystallin feature

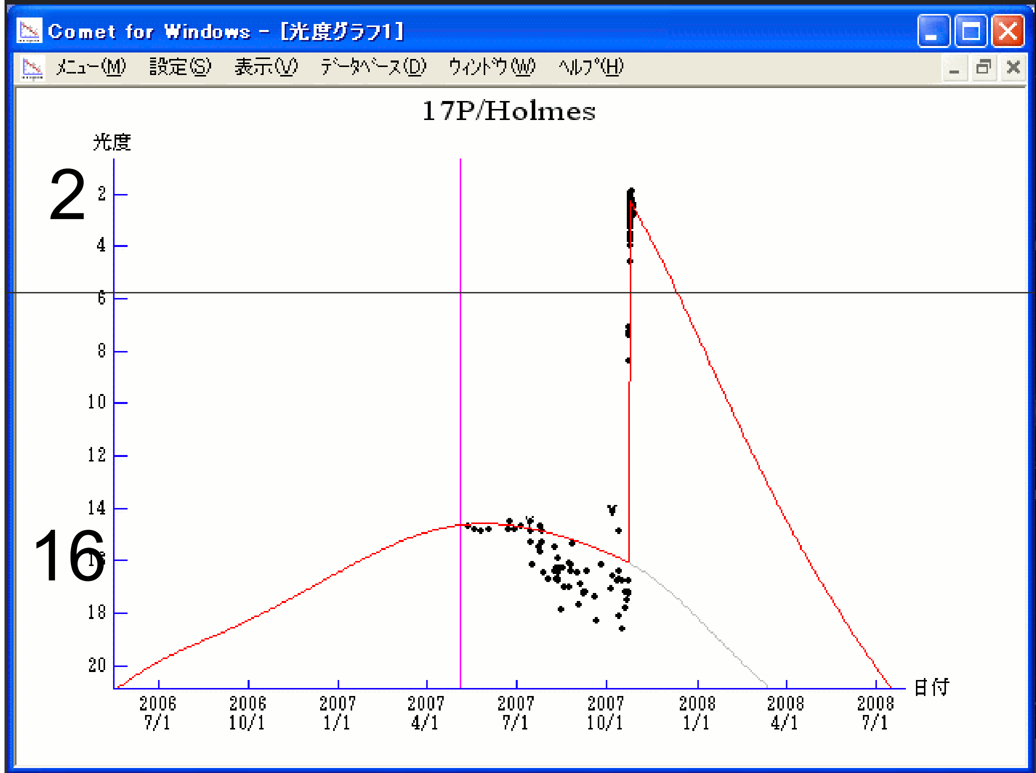
fragmentation

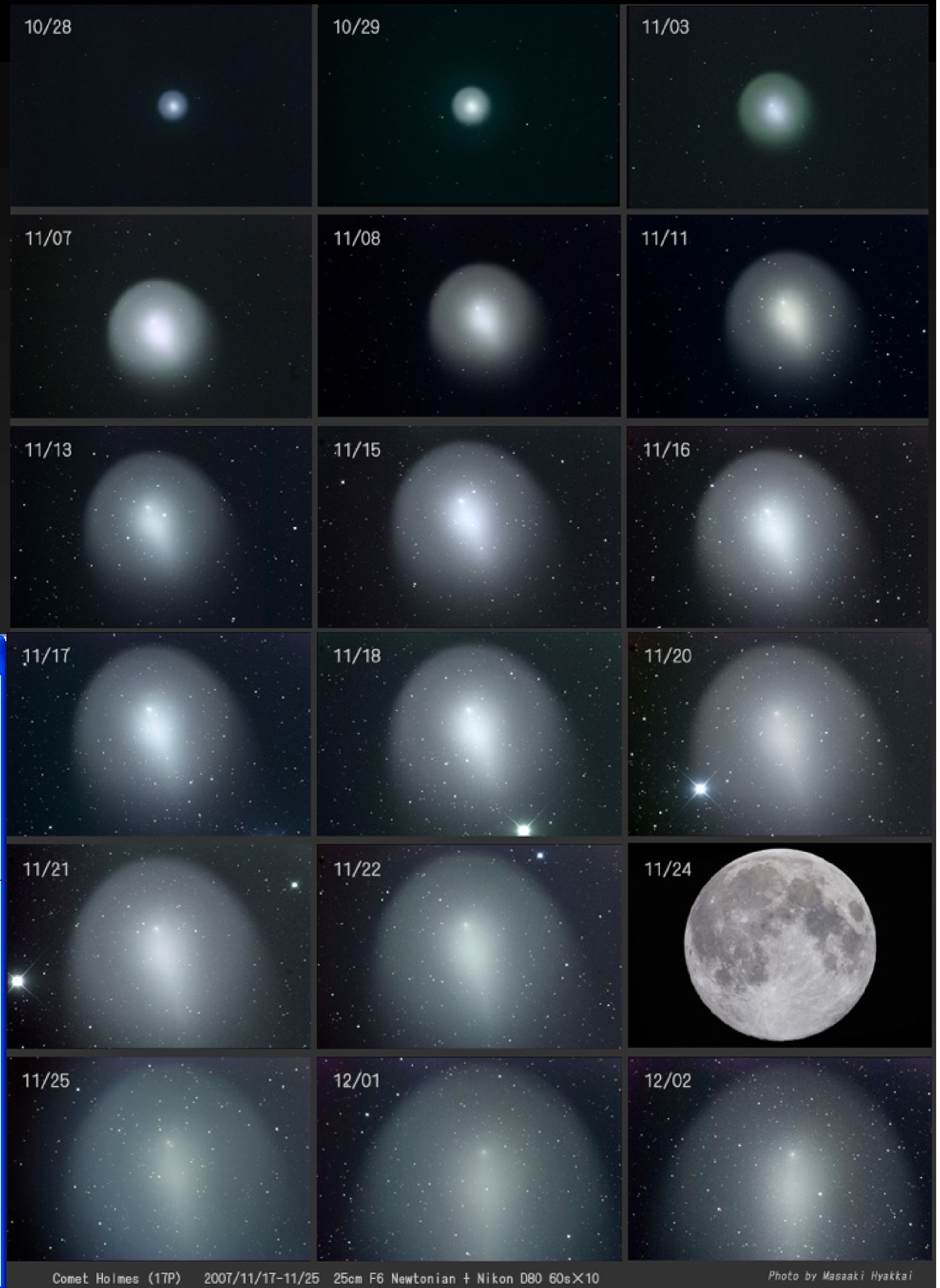
(Watanabe et al. in prep.)

17P/Holmes

outburst comet

(2007-10-24 UT)

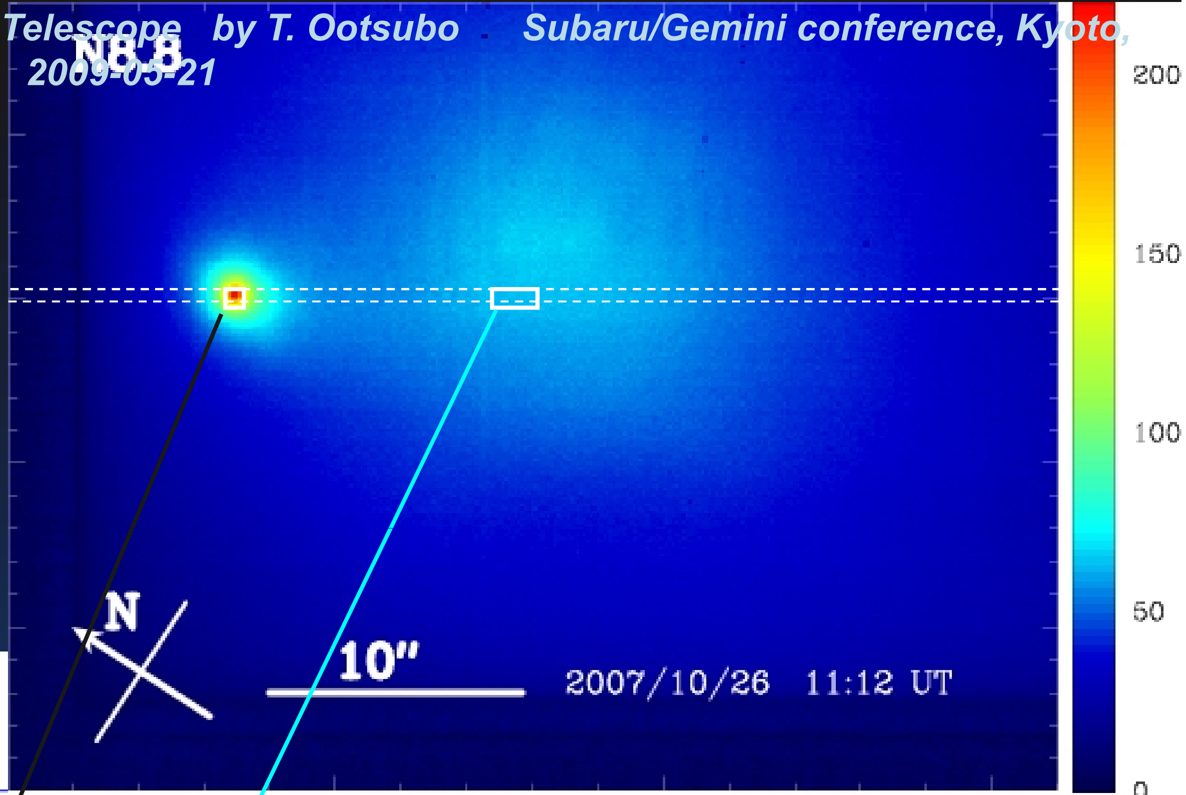


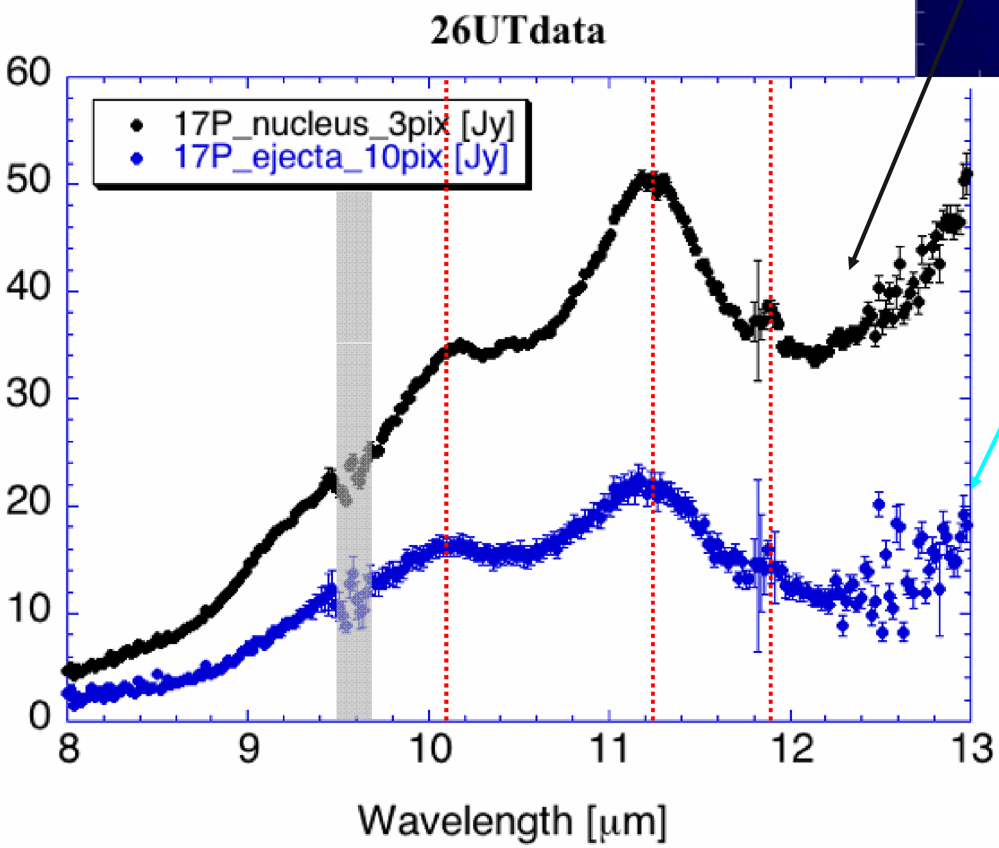


17P/Holmes

2007-10-26 UT
2 days after busrt

r = 2.45 AU, 👎 = 1.62 AU





(Watanabe et al. 2009)

Summary

- **We observed twelve comets by Subaru/COMICS in mid-IR.**
- **Subaru/COMICS has succeeded in detecting the clear crystalline silicate feature in several EC spectra, such as 9P/Tempel at the "Deep Impact" event and 17P/Holmes just after the explosive outburst phenomenon.**
- **There can be seen the slight difference between OCs and ECs in the dust mineralogy (especially crystalline-to-amorphoys ratio), but it is not a remarkable difference.**
- **It is suggested that OCs and ECs with different dynamic characteristics may have a similar origin or diffusive transportation was occurred in the early solar nebula.**
- **Collaborations between Mauna-Kea Telescopes are very effective for the comet science like Deep Impact event.**