Near- to mid-Infrared Observation of Supernovae with AKARI/IRC

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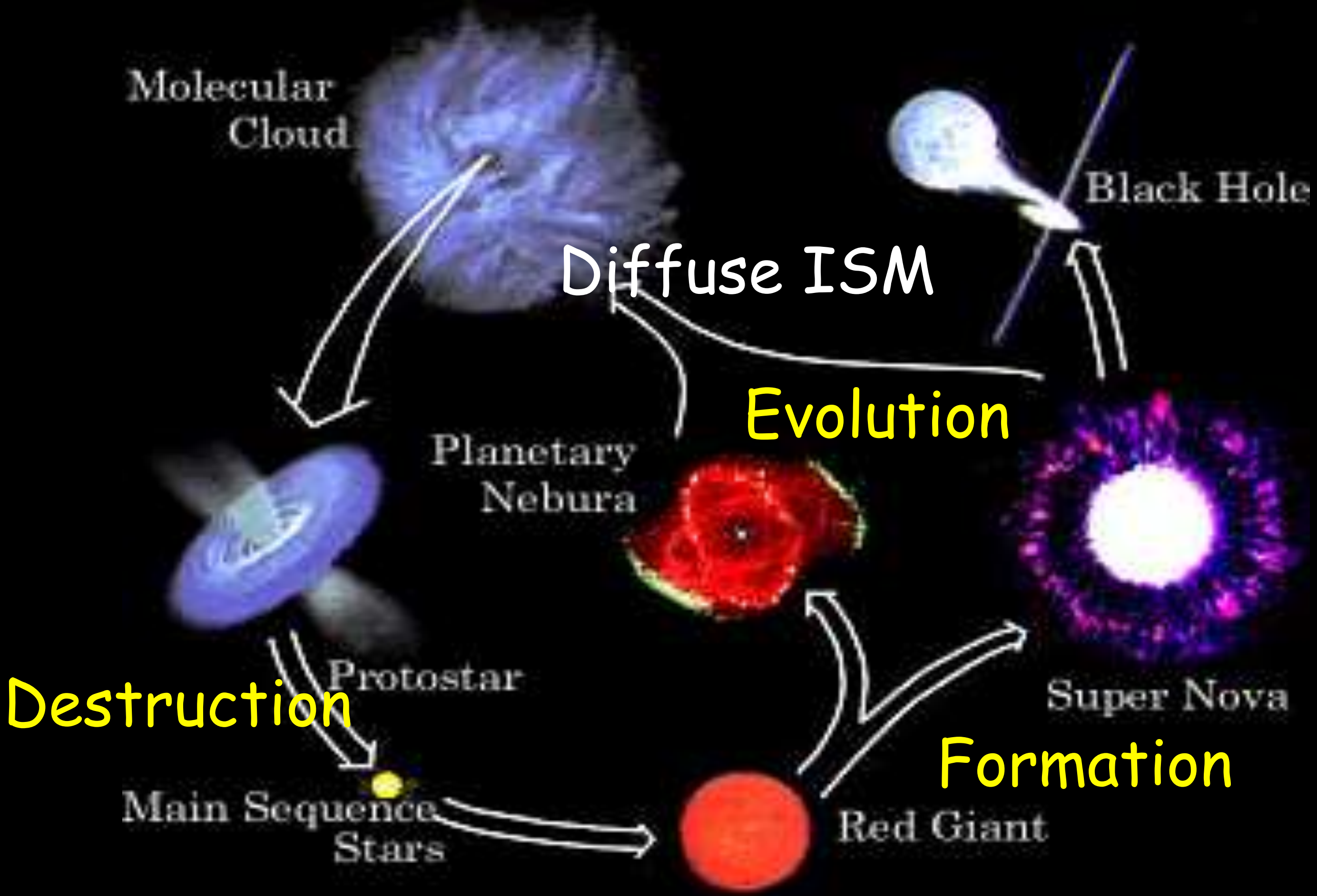


the life of interstellar dust
-- where the interstellar dust is formed
-- how they evolve in the interstellar space
-- how they enrich the universe

AKARI Mission

JAXA/ISAS mission
for infrared astronomy
with ESA participation

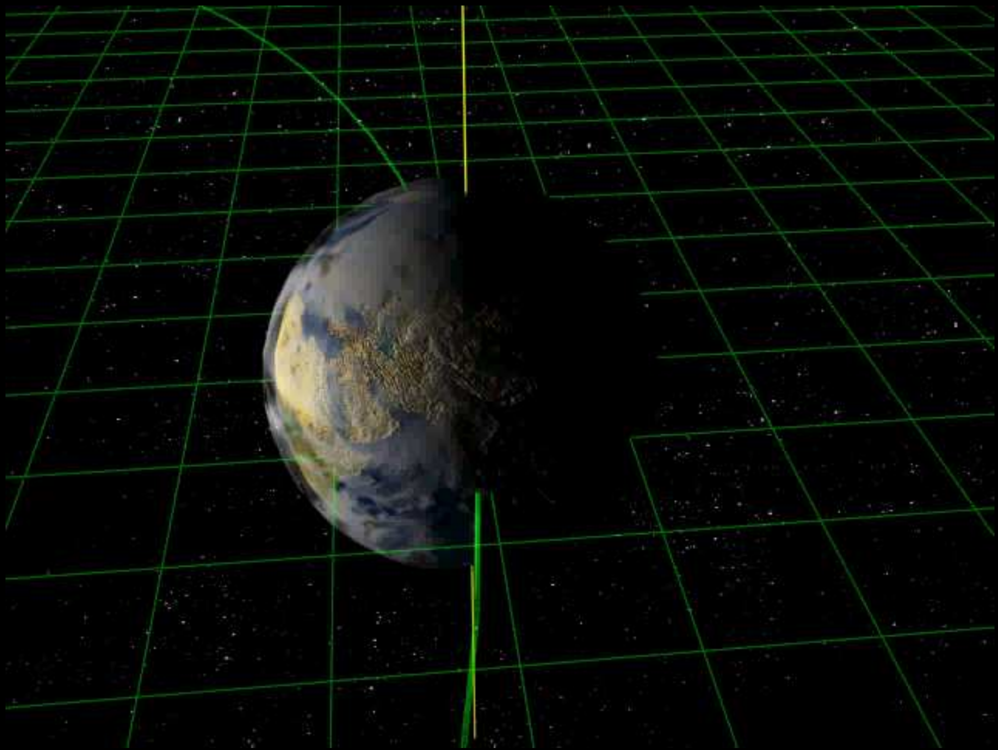
Telescope with 685mm SiC Mirror
cooled by 179l LHe
& mechanical coolers

2 instruments: IRC & FIS

Launched on Feb. 22, 2006
Successfully performed near-
to far-infrared observation

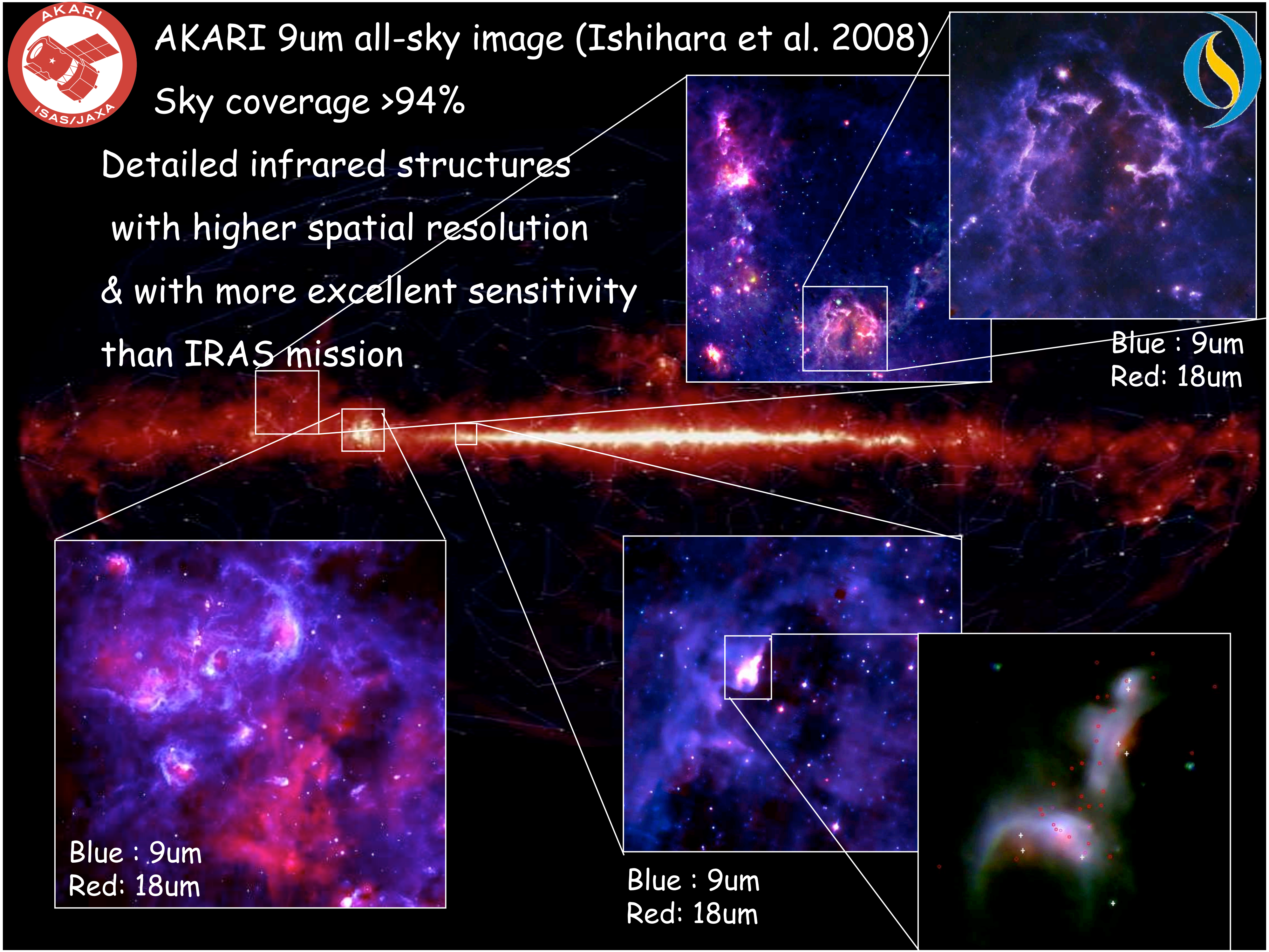
LHe: 2006 May - 2007 Aug
(phases I&II)

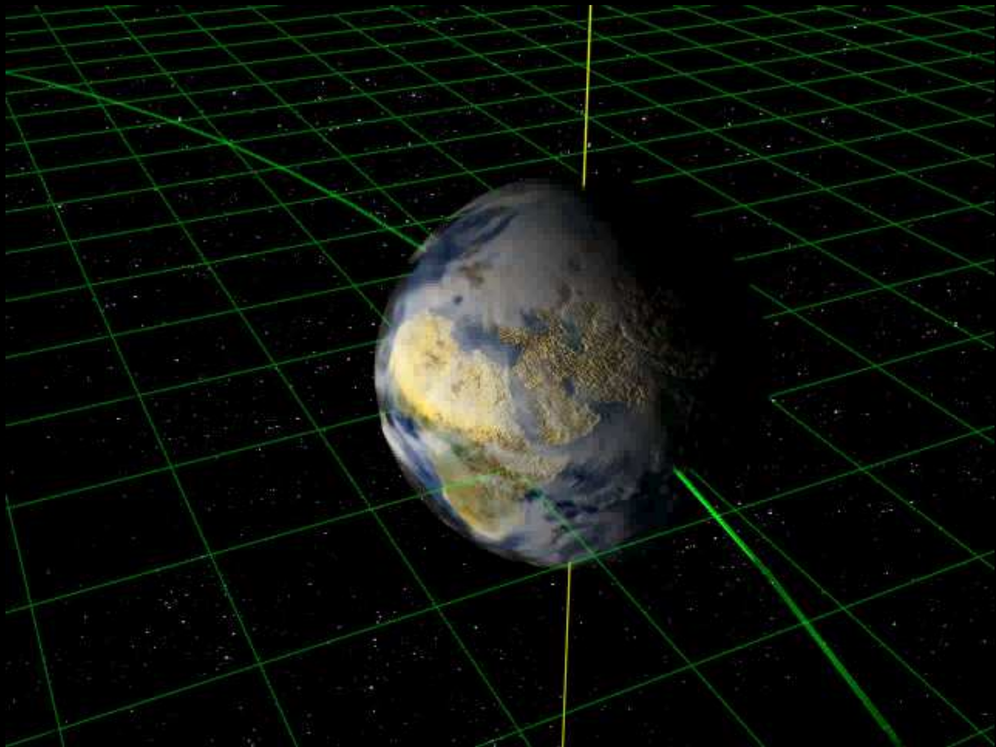
Warm mission: 2008 June –
(phase III; 2-5μm imag. & spec.)



The sun-synchronous polar orbit at the altitude of 700 km

The primary achievements of AKARI Mission:
All-sky survey at 9, 18, 65, 90, 140 & 160μm


AKARI 9um all-sky image (Ishihara et al. 2008)
Sky coverage >94%
Detailed infrared structures
with higher spatial resolution
& with more excellent sensitivity
than IRAS mission
Blue : 9um
Red: 18um
Blue : 9um
Red: 18um
Blue : 9um
Red: 18um
AKARI
ISAS/JAXA

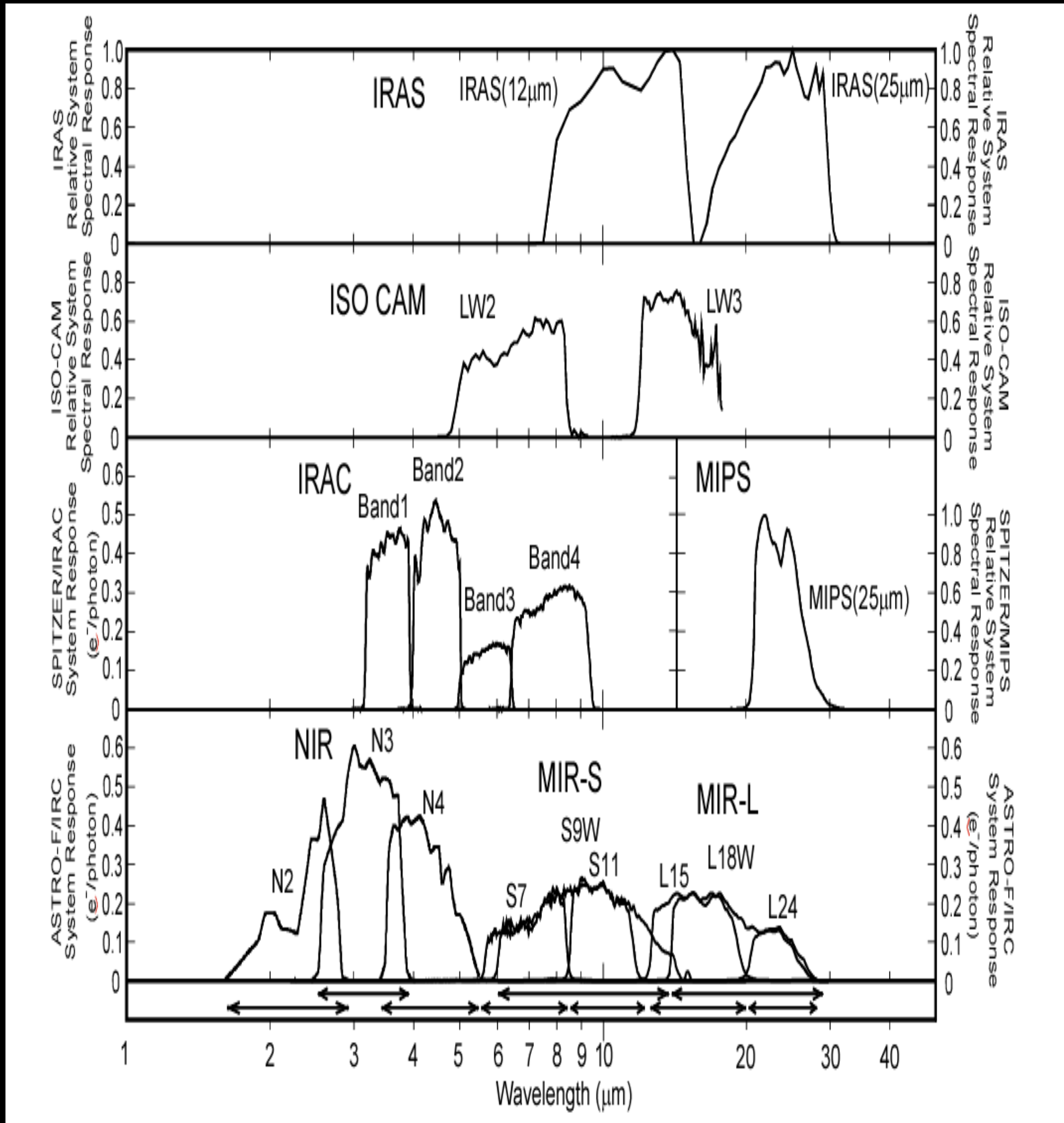


Pointed observations in 2 – 180μm with IRC & FIS
One pointed observation corresponds to ~10min integration
The observation chance of a certain target comes once in a 6months

More than 5000 pointed observations during Phases I&II
Still continuing the near-infrared pointed observations in Phase III

System spectral response curves of AKARI/IRC filters

Imaging filters



Infrared Camera (IRC)
-Near-infrared (NIR)
-Mid-Infrared-Short (MIR-S)
-Mid-Infrared-Long (MIR-L)

9 imaging filters (2-25μm)

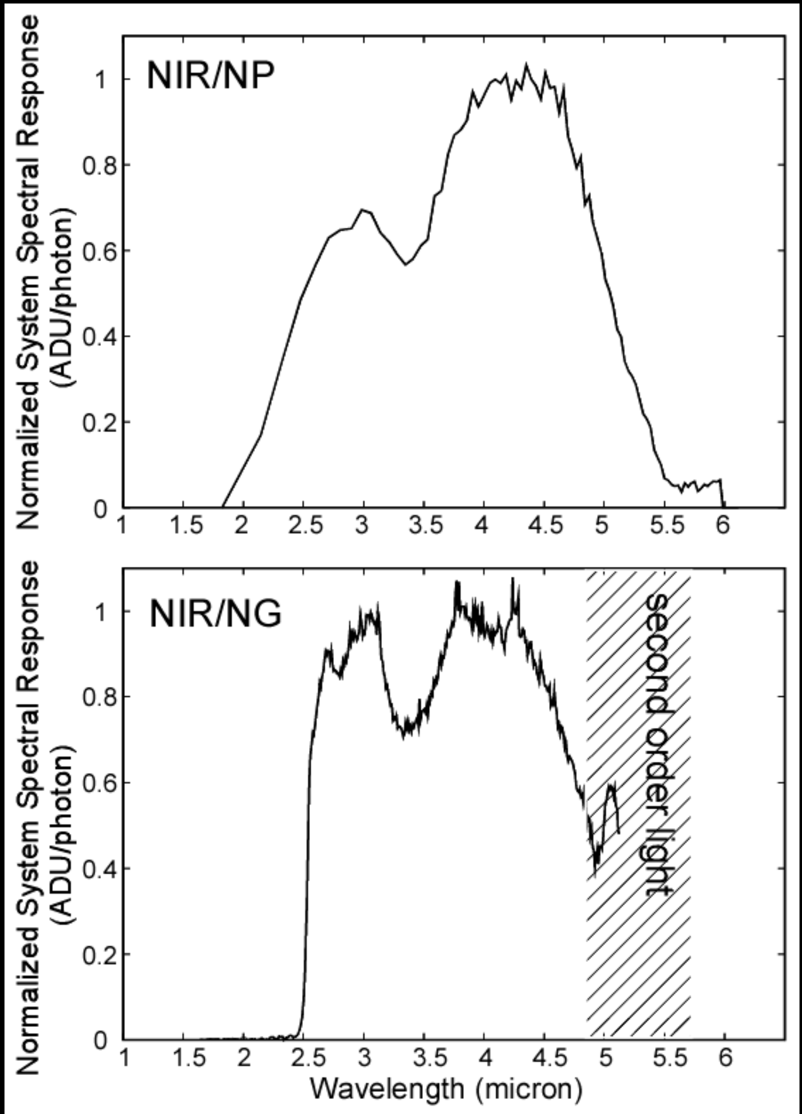
5-sigma sensitivity (μJy)

	AOT02	AOT03
N2	16	20
N3	16	19
N4	16	19
S7	74	91
S9W	76	93
S11	132	162
L15	279	341
L18W	273	335
L24	584	716

* Values in Phases I&II

System spectral response curves of AKARI/IRC NIR dispersers

NIR dispersers



AKARI's spectroscopic ability in the near-infrared in the warm mission is quite unique and valuable

Two Near-Infrared Dispersers
with different spectral resolution power
- Near-Infrared Prism (NP)
- Near-Infrared Grism (NG)

	Effective Coverage	Dispersion
NP	1.8μm-5.5μm	0.06 μm/pix at 3μm
NG	2.5μm-5.0μm	0.0097μm/pix

The 1-σ noise-equivalent flux
for slit-less spectroscopy at the ecliptic poles

	Phases I&II	Phase III
NP	~0.05mJy	~0.1mJy
NG	~0.1mJy	~0.2mJy

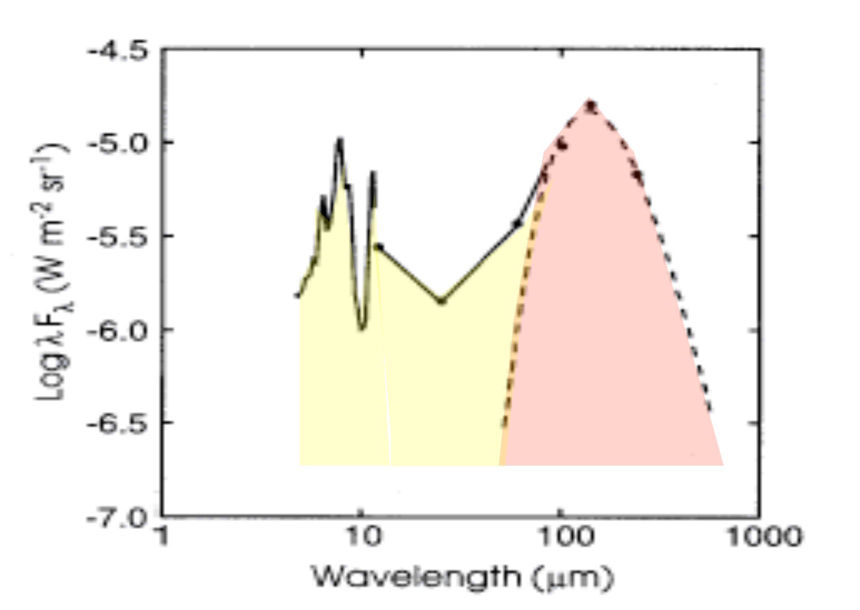
Infrared Emission of Interstellar dust

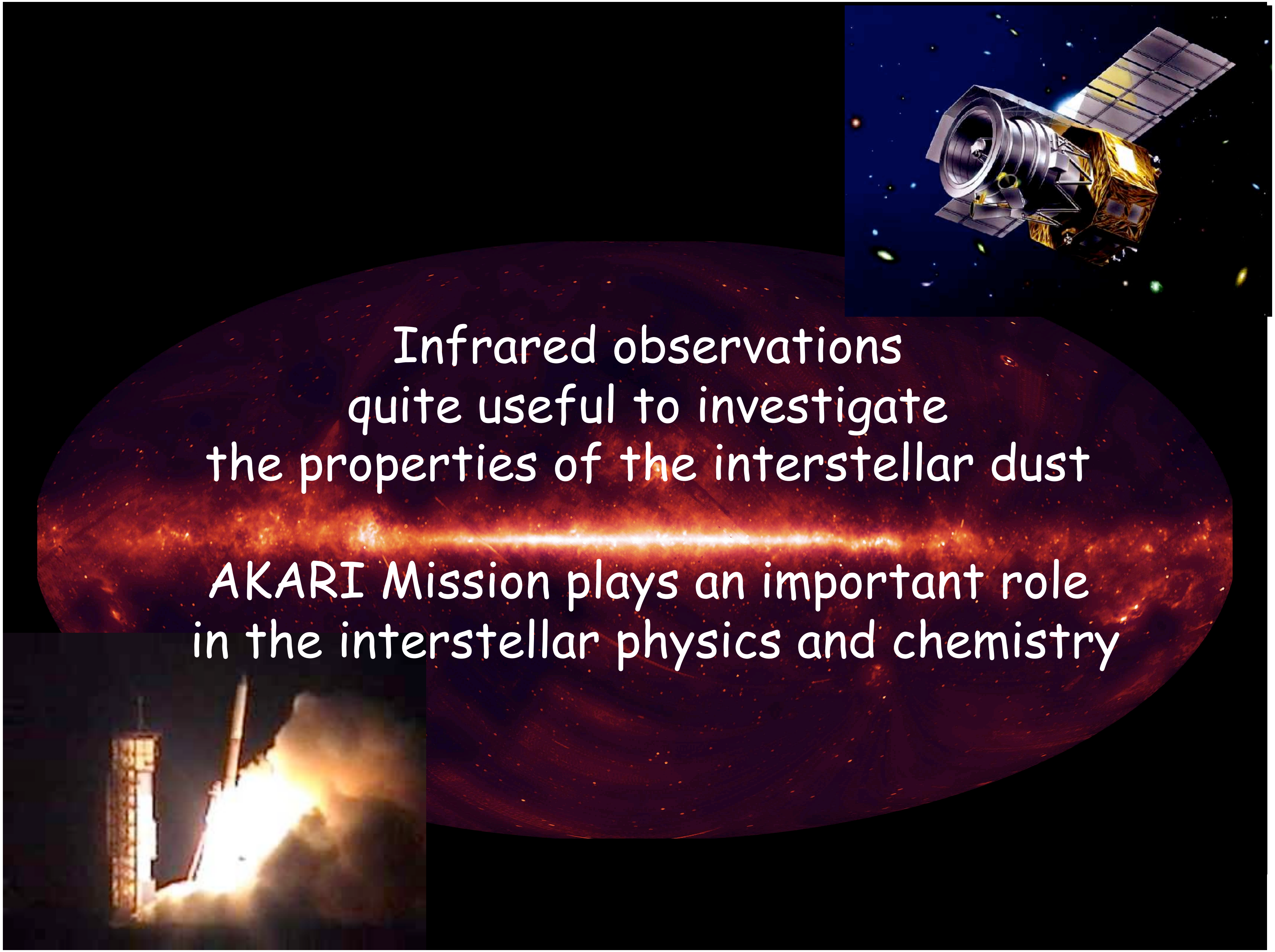
Interstellar dust grains; tiny solid particles with the size ranging from <1nm to >1μm
drifting in the interstellar space
powered by optical to UV photons
reradiates in the near- to far-infrared wavelengths

Far-Infrared (60μm~)
Thermal emission from submicron dust in radiation equilibrium
(BGs; ~100nm)

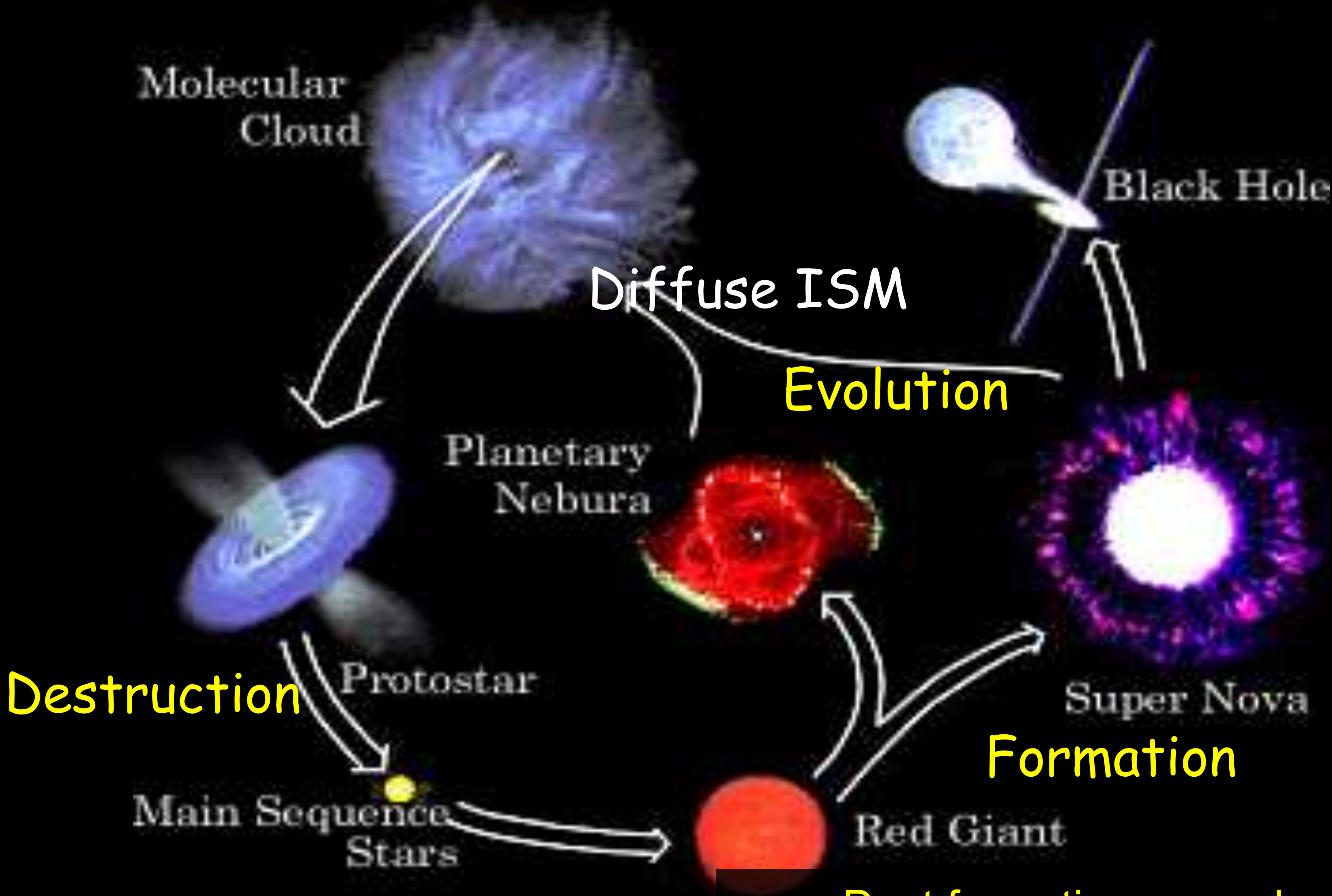
Near- to Mid-infrared (2μm~20μm)
amorphous silicate, amorphous carbons, etc
Ice band features
Polycyclic Aromatic Hydrocarbons
(PAHs; ~10Å, VSGs; 1~10nm)

Infrared emission from interstellar dust
in general interstellar environment of our Galaxy




Infrared observations
quite useful to investigate
the properties of the interstellar dust
AKARI Mission plays an important role
in the interstellar physics and chemistry

AKARI's latest results on the studies of interstellar dust



Dust formation around the core-collapse supernova

Interstellar dust budgets

Source	Carbon dust injection rate ($M_{\odot} kpc^{-2} Myr^{-1}$)	Silicate and metal dust injection rate ($M_{\odot} kpc^{-2} Myr^{-1}$)
C-rich giants	3.0	---
O-rich giants	---	5.0
Novae	0.3	0.03
SN type Ia	0.3	2.0
OB stars	---	---
Red supergiants	---	0.2
Wolf-Rayet	0.06	---
SN type II	2	10

(Tielens 2006)

Dust Formation in the core-collapse Supernovae

- Dust Formation in the ejecta of core-collapse supernovae (SNe)
  -> Important to explore the origin of dust in the early universe
  e.g., The amount of $0.1M_{solar}$ dust formation is needed for a core-collapse supernova to account for the dust content of high red-shift galaxies. (Morgan & Edmunds 2003)

- The dust condensation in the ejecta of core-collapse SNe is theoretically suggested (Kozasa et al.1991; Todini & Ferrera 2001)

- Observational Evidence for the dust formation in SN ejecta
  - Type II SN2003gd; $0.02M_{solar}$ (Sugerman et al. 2006)
    -> $4x10^{-5}M_{solar}$ (Meikle et al. 2007)
  - Type II SN1987A ; $7.5x10^{-4}M_{solar}$ (Ercolano et al.2007)
  - *Cas A* ; $0.003M_{solar}$ (Hines et al. 2004) or $0.02M_{solar}$ (Rho et al. 2004)
    → much smaller amount of dust formation

A gap still remains in produced dust mass in core-collapse SN ejecta between those observational results and theoretical prediction of 0.1 - $1M_{solar}$ (Nozawa et al. 2003)

Supernova 2006jc

- A peculiar Type Ib supernova (SN)
- discovered on 2006 October 9.75(UT) (Nakano et al.2006) in UGC4904
- The progenitor had experienced a LBV-like luminous outburst event 2 years prior to the SN event (Pastorello et al.2007; Foley et al. 2007)

Evidence for Dust Formation in the SN ejecta

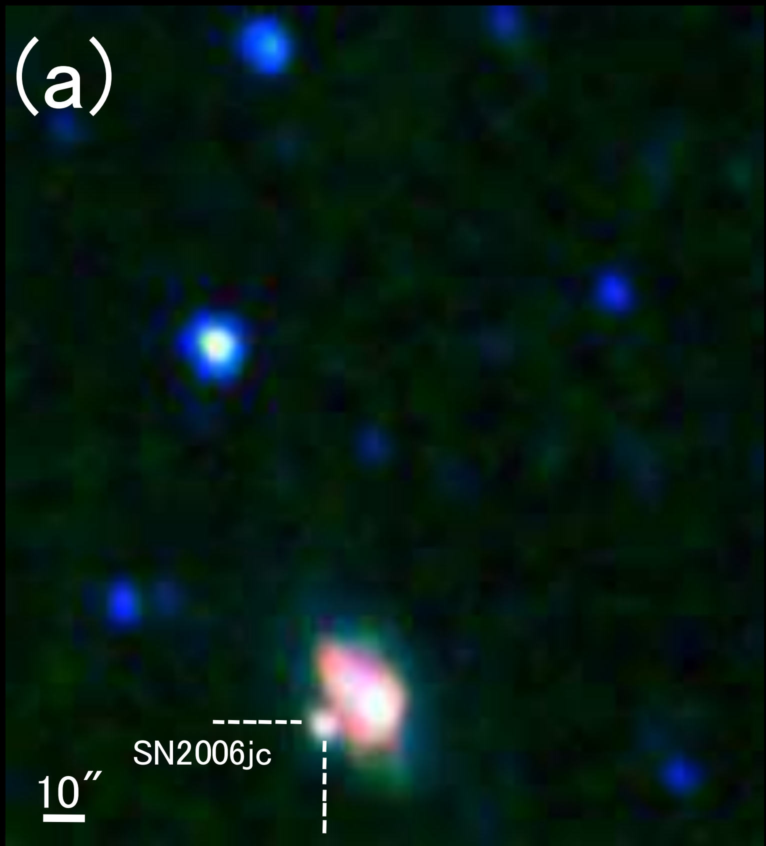
- Presence of an continuum excess emission at red/near-infrared
- The fading of red-shifted side of the narrow He I emission lines
- Increase in the optical extinction

These characteristics are observed simultaneously between 51 and 75 days after the brightness peak (Smith et al. 2007)

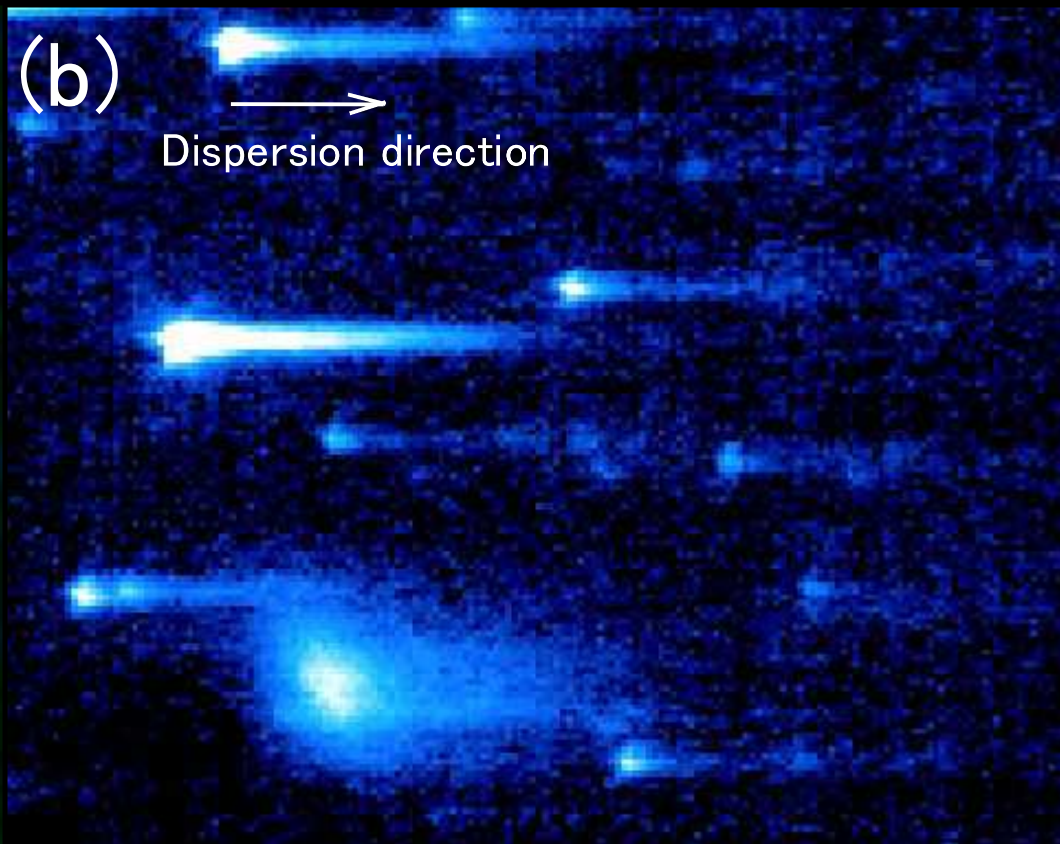
Observation of SN2006jc with AKARI/IRC

- Observation ID: 5124071 (AOT04), 512472(AOT02b)
- 00:36:22(UT) and 02:15:47(UT) on 29 April 2007 (epoch of 220 days)

AKARI Infrared Camera (IRC)
- NIR NP (prism 2-5.5μm) & N3 (3μm)
- MIR-S S7 (7μm), S9W(9μm), S11 (11μm)

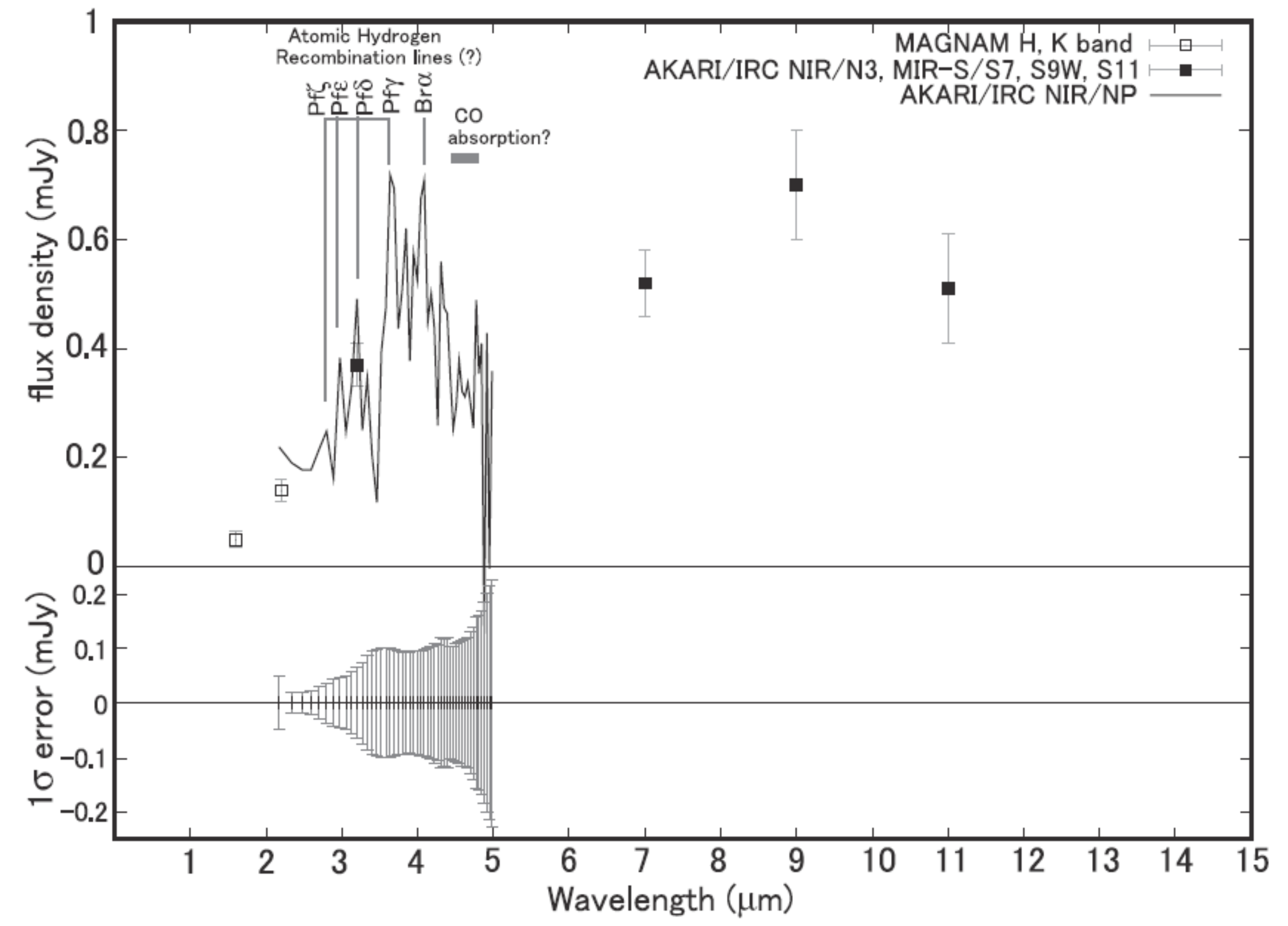


RGB color image of SN2006jc made with NIR/N3(blue), MIR-S/S7 (Green), and S11 (red) bands.



NIR/NP (prism 2-5.5μm) data of SN2006jc

Near to Mid-Infrared Spectral Energy Distribution of SN2006jc at the epoch of 220 days

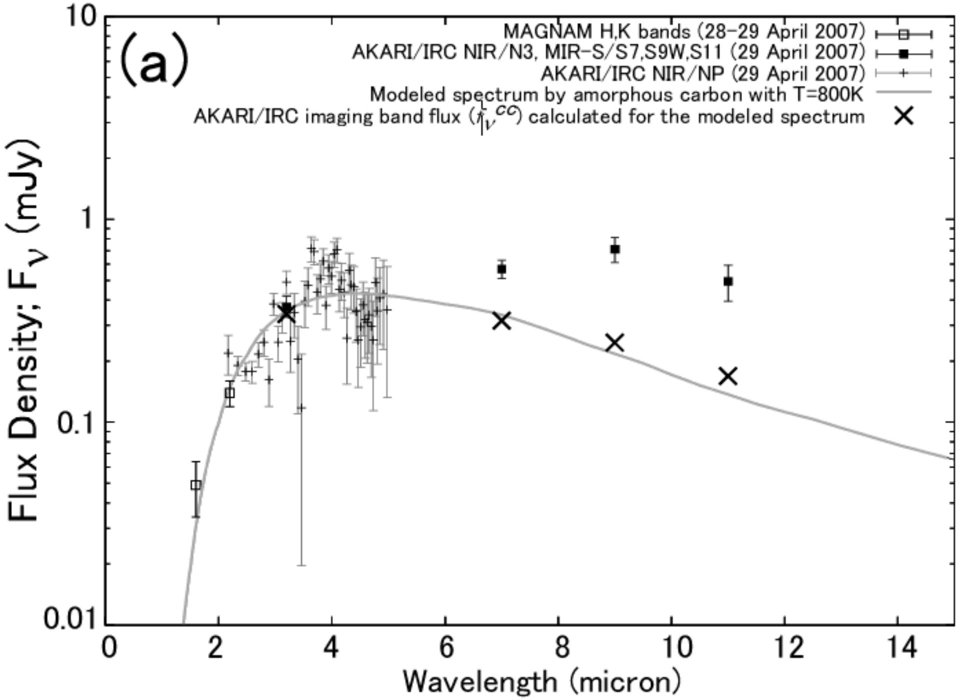


Near Infrared spectrum of SN2006jc

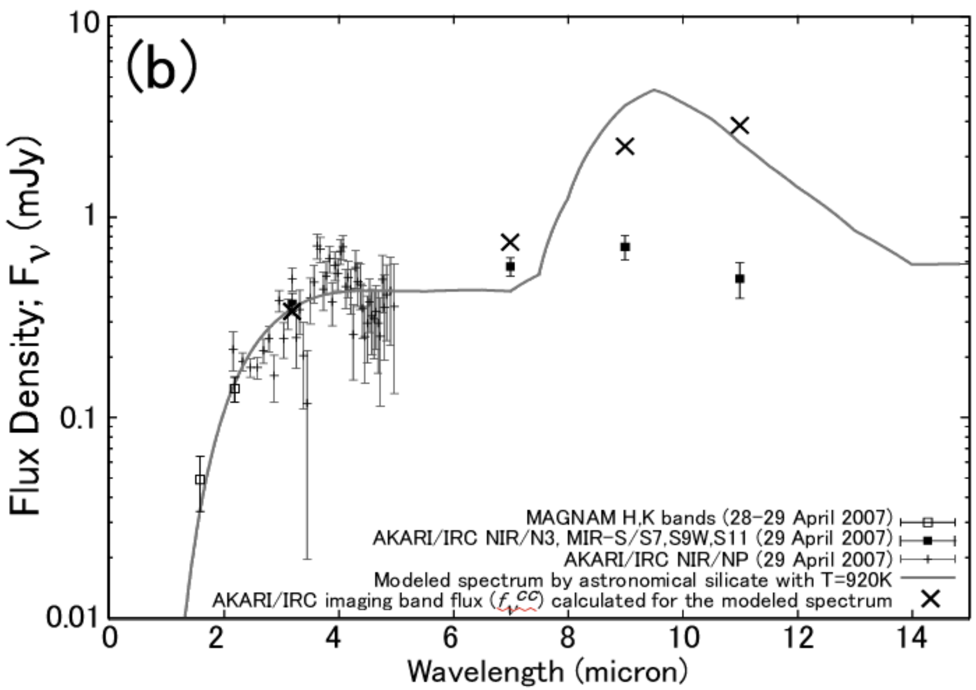
Spherical dust grains of a certain kind X
A uniform particle radius a_X, a total mass of M_X and the equilibrium temperature of T_X(K)
Located at a distance of R from the observer
Optically thin

$$f_\nu^X(\lambda) = M_X \left(\frac{4}{3}\pi\rho_X a_X^3\right)^{-1} \pi B_\nu(\lambda, T_X) Q_X^{abs}(\lambda) \left(\frac{a_X}{R}\right)^2$$

(a) Amorphous carbons (X=a.car.)



(b) Astronomical silicate (X=a.sil.)

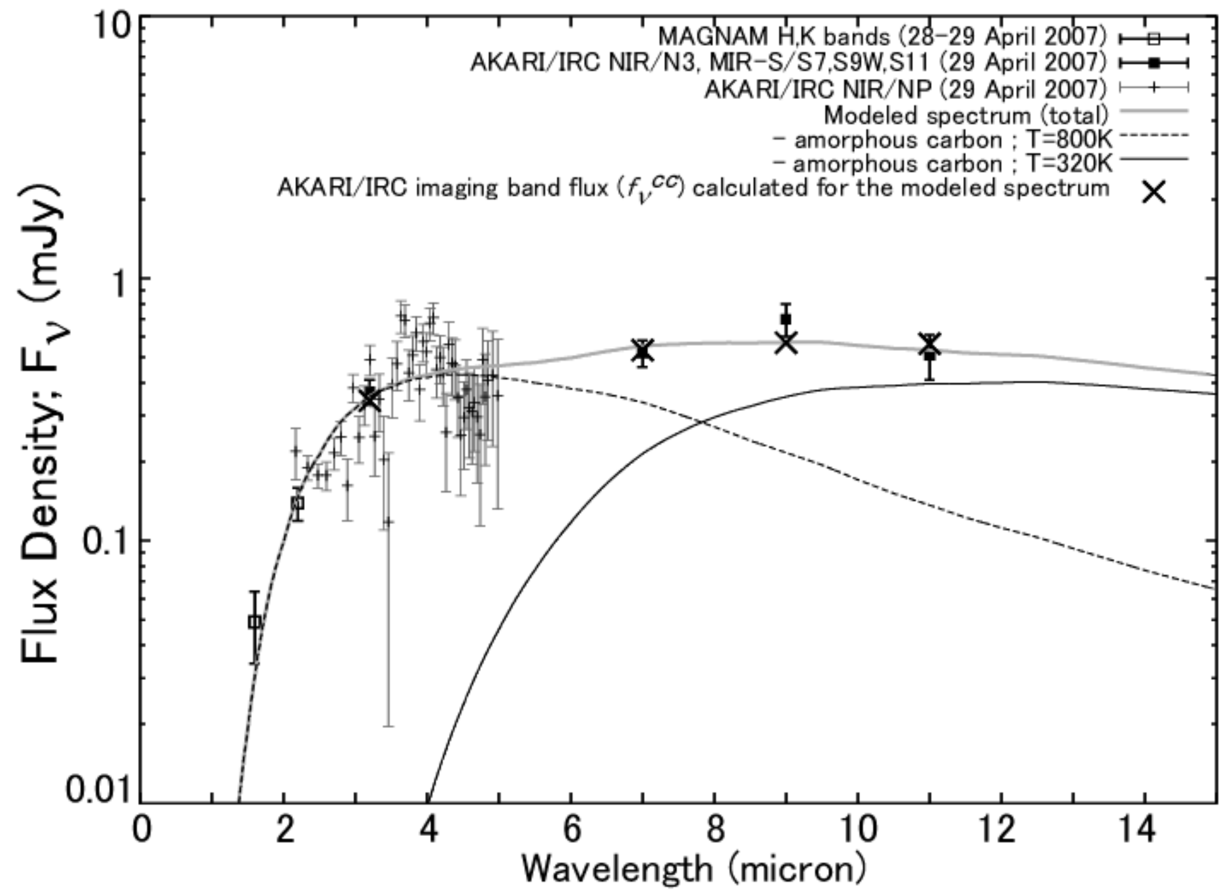


$T_{a.car.}$ = 800±10 (K)
$M_{a.car.}$ = 6.9±0.5 × 10^{-5} M_{solar}

$T_{a.sil.}$ = 920±10 (K)
$M_{a.sil.}$ = 4.2±0.3 × 10^{-4} M_{solar}

Excess emission in the mid-infrared (Two Temperature Amorphous Carbon Model)

X_1=hot amorphous carbon, X_2=warm amorphous carbon



$T_{hot.car.}$ = 800±10 (K)

$M_{hot.car.}$ = 6.9±0.5 x 10^{-5} M_{solar}

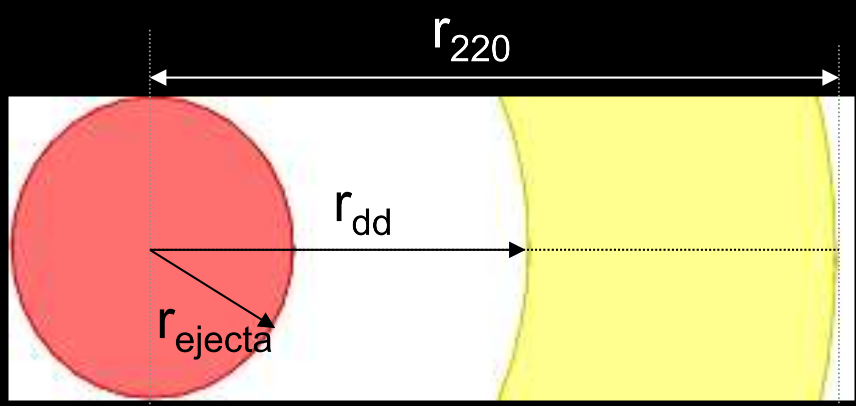
Newly formed dust in the ejecta of SN2006jc

$T_{warm.car.}$ = 320±10 (K)

$M_{warm.car.}$ = $2.7^{+0.7}_{-0.5}$ x 10^{-3} M_{solar}

Pre-existing circum-stellar dust formed in the mass loss wind associated with the Wolf-Rayet Stellar activity (Williams et al.1992; Waters et al.1997; Molster et al.1999; Voors et al.2000)

Geometry of Dust around the SN2006jc



r_{220} : the distance that the light travels for 220 days
~ 5.7×10^{12} km

r_{dd} : the radius of the dust-depleted region made by the irradiation of shock breakout
assuming the shock breakout luminosity of $L_{sb} = 10 \times L_{peak} \sim 7 \times 10^{43}$ erg s^{-1}
and the evaporation temperature of $T_{ev.} = 1800$K
~ 2×10^{12} km

r_{ejecta} : the distance that the ejecta travels for 220 days
assuming the ejecta velocity to be 3×10^4km/s (Tominaga et al. 2008)
~ 5.7×10^{11} km

If the total mass $M_{hot.car.} = 6.9 \pm 0.5 \times 10^{-5} M_{solar}$ of spherical amorphous carbon grains with a single radius of a=0.01μm are contained uniformly within a sphere with r_{ejecta}, the optical depth at 3.2μm becomes $\tau(3.2) = 4.9 \times 10^{-2}$.

→ consistent with the assumption that the dust emission is optically thin.

Spitzer Observations of SN2006jc
（Mattila et al. 2008, MNRAS, ）

Spitzer IRAC photometric data of SN2006jc at the epoch ~230 days;

The dust formation in the cool dense shell (CDS)
produced by the interaction of the ejecta onward-shock
with a dense shell of the circumstellar material
→ $3 \times 10^{-4} M_\odot$ of amorphous carbon as the mass of newly formed dust

Excess emission in the mid-infrared
→ Dust condensation in the mass loss wind associated with the prior events to the SN explosion

Dust formation
around the core-collapse supernova 2006jc

Near- to Mid-infrared observations of SN2006jc on 220 days with AKARI/IRC
-> We succeeded in obtaining the thermal emission spectrum of newly formed dust in the ejecta of the type Ib supernova for the first time

The near- to mid-infrared spectrum of SN2006jc at the epoch of 220days is well explained by the two temperature amorphous carbon model

(i) Hot amorphous carbon ($T_{hot.car.}$ = 800±10 K, $M_{hot.car.}$ = 6.9±0.5 x 10^{-5} M_{solar})
→ newly formed amorphous carbon in the ejecta of SN2006jc

(ii) Warm amorphous carbon ($T_{warm.car.}$ = 320±10 K, $M_{warm.car.}$ = $2.7^{+0.7}_{-0.5}$ x 10^{-3} M_{solar})
→ Pre-existing circum-stellar dust formed in the mass loss wind associated with the Wolf-Rayet Stellar activity

The dust mass of the hot amorphous carbon (6.9±0.5 x 10^{-5} M_{solar}) is more than 3 orders of magnitude smaller than the amount needed for a core collapse supernova to contribute efficiently to the early-Universe dust budget (i.e., ~1 M_{solar}: Morgan & Edmunds 2003)

Dust condensation not only in the SN ejecta itself but also in the mass loss wind associated with the prior events to the SN explosion could make a significant contribution to the dust formation by a massive star in its whole evolutional history

Future programs

Near-infrared imaging and spectroscopy of several supernovae including SN2008D, SN2008S, SN2008ax, SN2008bo with AKARI/IRC

Identifications	Observation date (UST)	Epoch (days)	Observation mode N2	N3	N4	NP	NG
SN2006jc	29, Apr., 2007	~220	--	○	--	○	○
	28-29, Apr., 2008	~585	--	○	○	○	--
SN2008D	30, Apr., 2008	~110	--	○	○	○	--
	01-02, Nov., 2008	~290	○	○	○	○	--
SN2008S	15-17, Jun., 2008	~140	--	○	○	○	○
	18, Dec.,2008	~320	--	○	--	○	--
SN2008ax	07-08, Jun., 2008	~100	--	○	○	○	○
SN2008bo	06-07, Sep., 2008	~160	○	○	○	○	--
	09-10, Mar., 2009	~340	○	○	○	○	--

White; observations executed

Blue ; observations scheduled

Future programs

AKARI Phase 3 Open Time Program
Near-IR Spectroscopy of Galaxies; Waiting for Supernovae momentarily (NEWSY)
(P.I.; Sakon, I.)

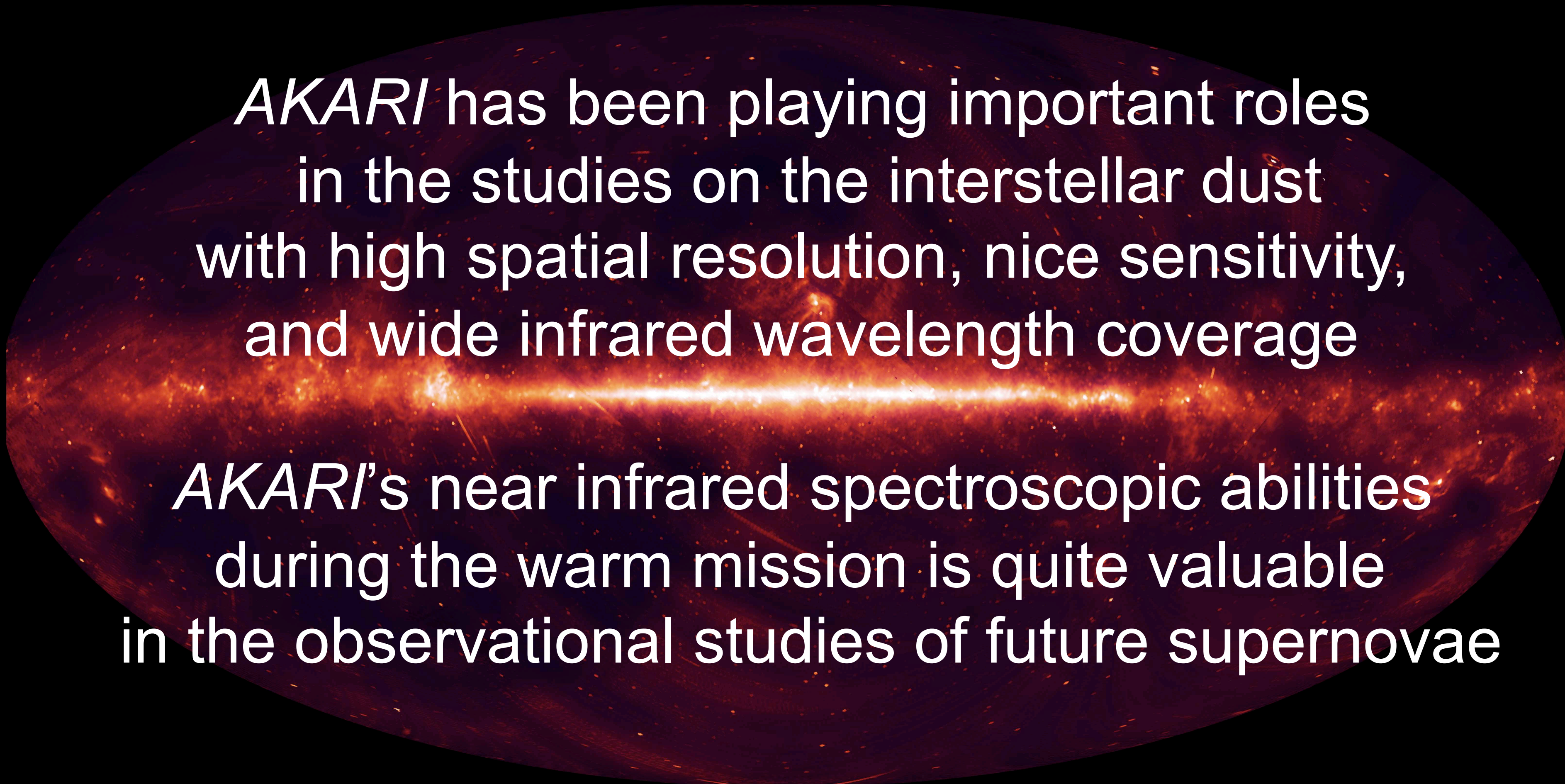
AKARI/IRC is, so far, the only instrument that is capable of obtaining the near-infrared spectra (covering from 2 to 5.5μm) of supernovae within 6 months after explosion.

Constructing a near-infrared slit-less spectroscopic database of nearby galaxies in preparation for a future supernova there.

The obtained database is directly used to estimate the spectroscopic patterns of the host galaxy and to obtain the spectrum of supernova with higher accuracy once the supernova explosions occurs in the future

Nearby Galaxies (<30Mpc) with relatively higher supernova rate are selected;
NGC722, NGC908, NGC1097, NGC1187, NGC1313, NGC1365, NGC1448, NGC1559, NGC2207, NGC2276, NGC2403, NGC2841, NGC3169, NGC3184, NGC3198, NGC3631, NGC3646, NGC3690, NGC3810, NGC3953, NGC4157, NGC4939, NGC5033, NGC5161, NGC5468, NGC6754, NGC6943, NGC6946, NGC6951, IC5201, ESO576-40

Summary



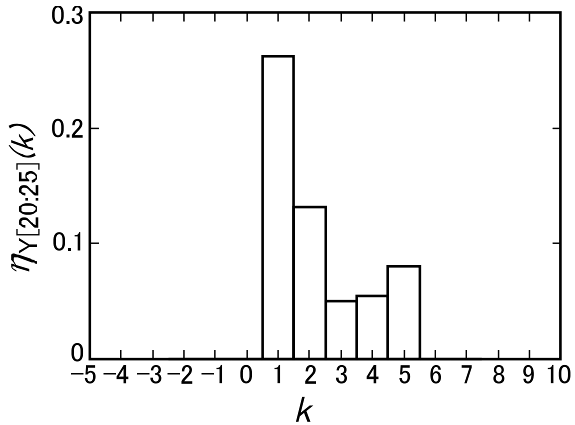
AKARI has been playing important roles
in the studies on the interstellar dust
with high spatial resolution, nice sensitivity,
and wide infrared wavelength coverage

AKARI's near infrared spectroscopic abilities
during the warm mission is quite valuable
in the observational studies of future supernovae

Data Reduction Procedure for Near-Infrared Spectrum of SN2006jc

Subtraction of the UGC4904 component is crucial to obtain the pure spectrum of SN2006jc

$$I^{UGC4904}_{Y[20:25]}(X) = \sum_{k=-\infty}^{\infty} \eta_{Y[20:25]}(k) I_{Y[28:29]}(X-k)$$



$$S^{UGC4904}_{Y[20:25]}(X) = \sum_{k=-\infty}^{\infty} \eta_{Y[20:25]}(k) S_{Y[28:29]}(X-k)$$

$$S^{SN2006jc}_{Y[20:25]}(X) = S_{Y[20:25]}(X) - S^{UGC4904}_{Y[20:25]}(X)$$