SPICA Mission Requirement Document (MRD)

ver. 3.5 draft

Explanatory presentation

19 May 2009

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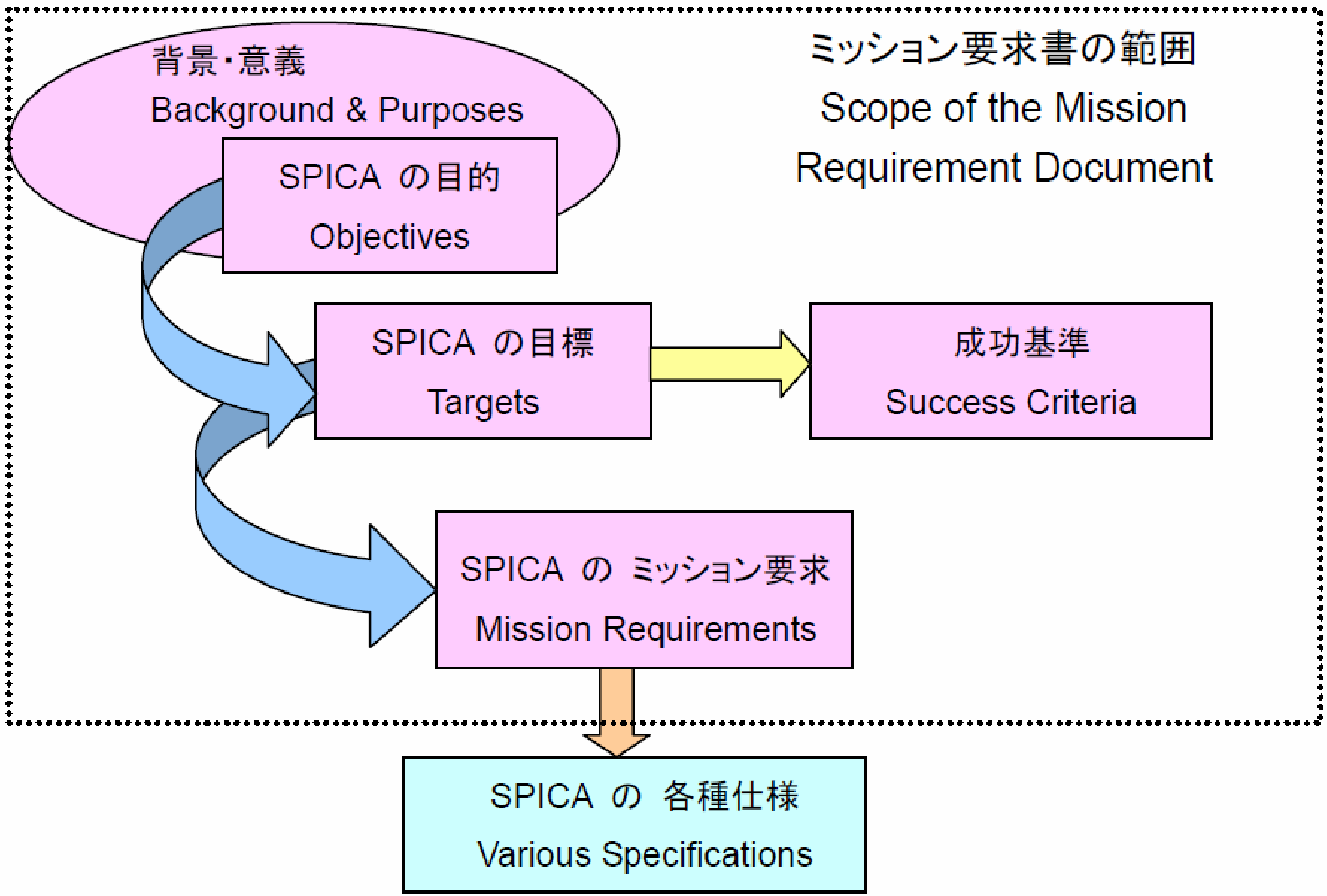
Scope of SPICA MRD

- The MRD clarifies the ***objectives*** of the SPICA mission.
- The ***objectives*** of the mission are more concretely expressed by various ***scientific targets*** (plus also technical purposes).
- Based on these ***targets***, the ***mission requirements***, such as required specifications of the mission instrumentations, scientific operations etc. are defined.
- Also the ***success criteria***, by which the evaluation of the mission achievement will be addressed, are clearly described.
- The ***mission requirements*** described here will give the baseline of the study of the system requirements.
- In the future, this document will also be used to confirm the development status, system performance, and operational results on orbit etc. are well in-line with the ***mission requirements*** described in this document.
- The description in this document may be updated depending on the change in the stake-holder’s opinions or external conditions, and in such case this document will be used as the source and reference document to estimate the effects on the mission achievement.

The SPICA Mission Requirement



SPICAの科学目的達成に向けてのアプローチ法

Approaches to perform SPICA Scientific Objectives

《銀河誕生のドラマ》をさぐる

《惑星系のレシピ》をさぐる

[1]
銀河の誕生と進化過程の解明
Resolution of Birth and Evolution of Galaxies

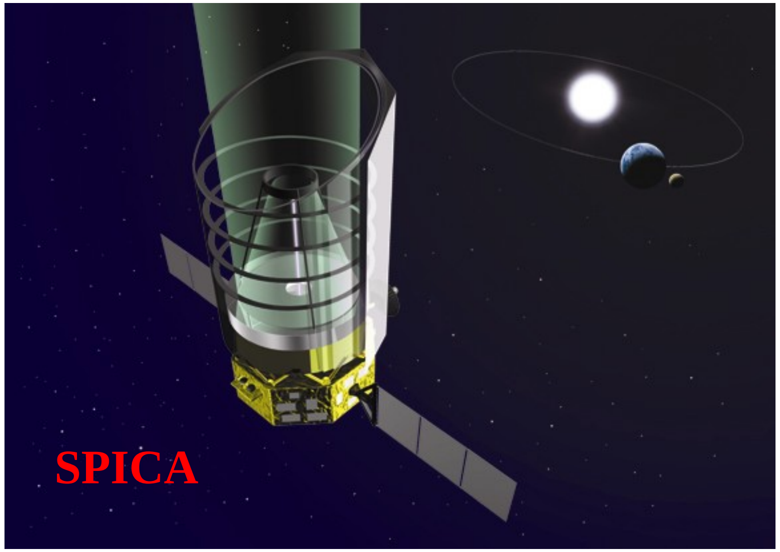
[2]
銀河星間空間における物質輪廻の解明
The Transmigration of Dust in the Universe

[3]
惑星系形成過程の総合理解
Thorough Understanding of Planetary System Formation

遠方宇宙／初期宇宙
Distant/Early Universe

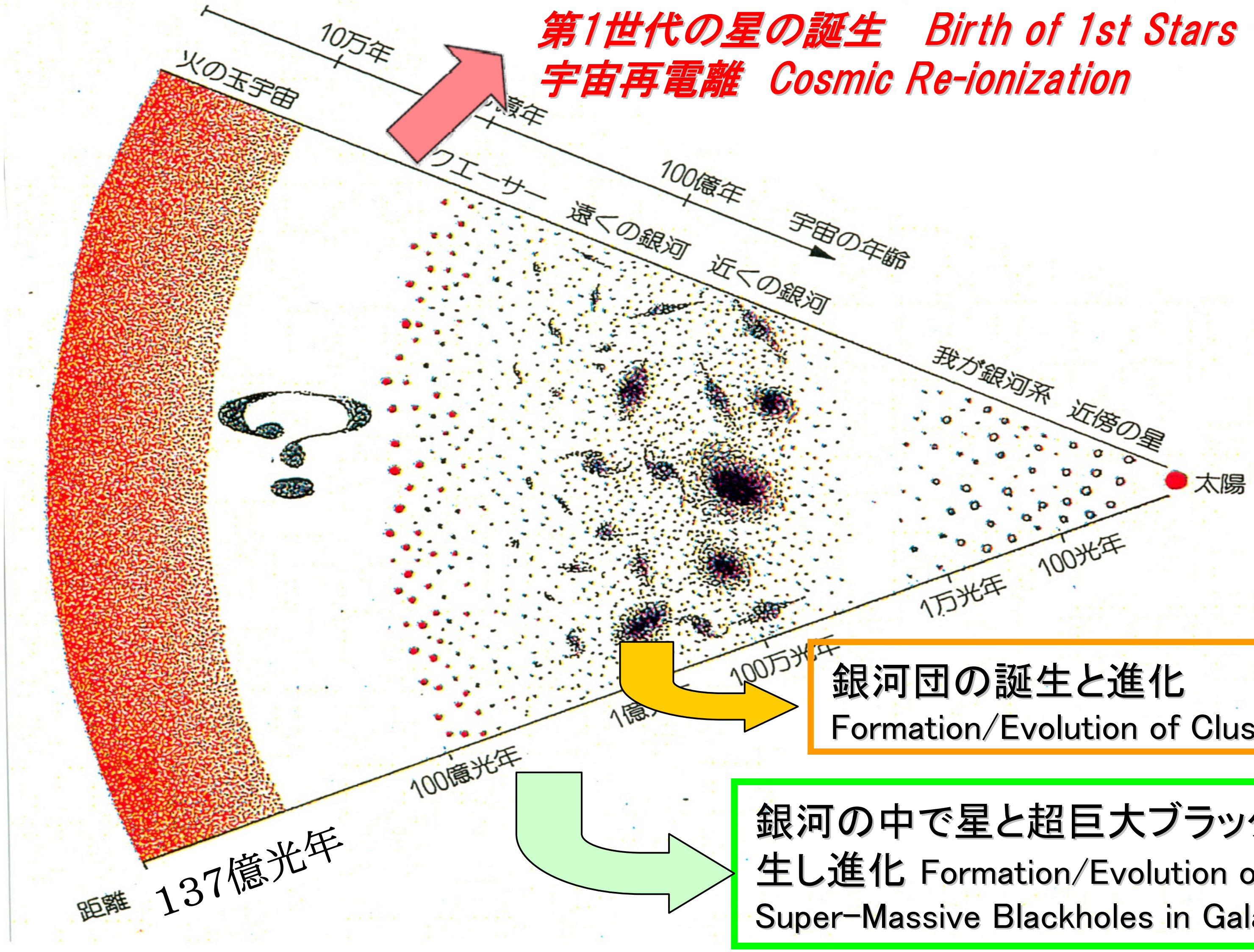
近傍宇宙（恒星系）
Local Universe/Stellar system

Major Objective [1]
銀河の誕生と進化過程の解明
Resolution of Birth and Evolution of Galaxies

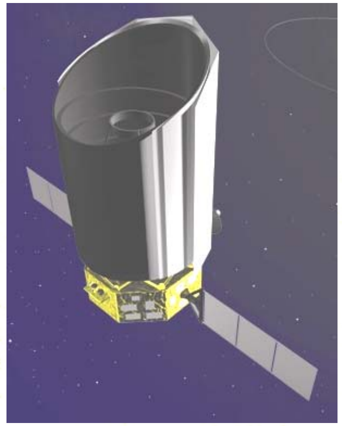


銀河の誕生と進化過程の解明
Resolution of Birth and Evolution of Galaxies

第1世代の星の誕生　Birth of 1st Stars
宇宙再電離　Cosmic Re-ionization



SPICA



銀河団の誕生と進化
Formation/Evolution of Cluster of Galaxies

銀河の中で星と超巨大ブラックホールが誕生し進化 Formation/Evolution of Stars & Super-Massive Blackholes in Galaxies

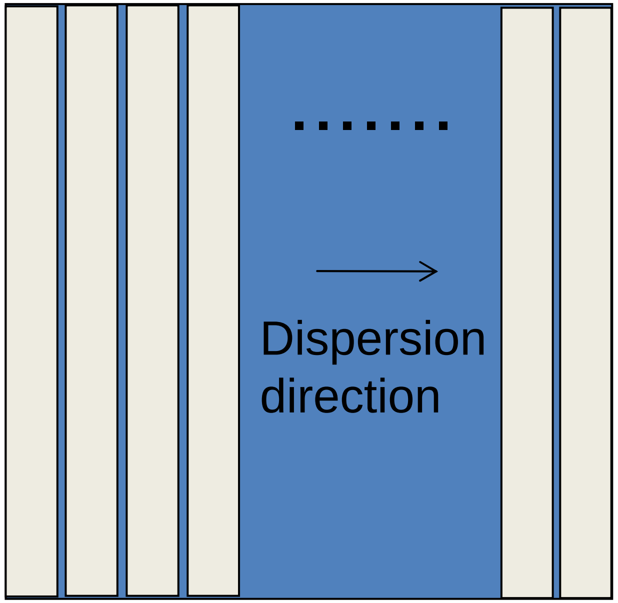
Extragalactic Science :Objective #1

- 科学目的 Objective
  - 銀河の誕生の解明のために重要な天体である宇宙再電離期の「種族III天体」（第一世代の星）の検出に挑む。
  - We will discover “population III” objects (first generation of stars) at re-ionization epoch, which play an important role in the understanding of galaxy formation processes.
- 科学目標 Target
  - 「種族III天体」の候補である遠方（赤方偏移7以上）、（低金属量10^{-4}以下）の星からの電離輝線を、放射エネルギーが赤方偏移した赤外線領域の分光観測で検出する。これにより種族III天体の存在を明らかにする。さらに「種族III天体」の形成時の分子雲冷却にかかわる水素分子輝線（赤方偏移3以上）を赤外線分光観測で探査し「種族III天体」形成の証拠を探る。
  - We will search for redshifted ionization lines (z>7) from low-metal objects (less than 10^{-4}) with mid-IR spectroscopy, by which we intend to prove the existence of population III objects. We also investigate the formation of population III objects at z>3 through emission lines from hydrogen molecules -- important cooling lines of primeval molecular clouds -- using far-infrared spectrograph.

遠赤外線分光装置 BLISS 中間赤外線撮像・低分散分光装置 MIRACLE

Hα at z>7 will be detectable with MIRACLE/SPICA

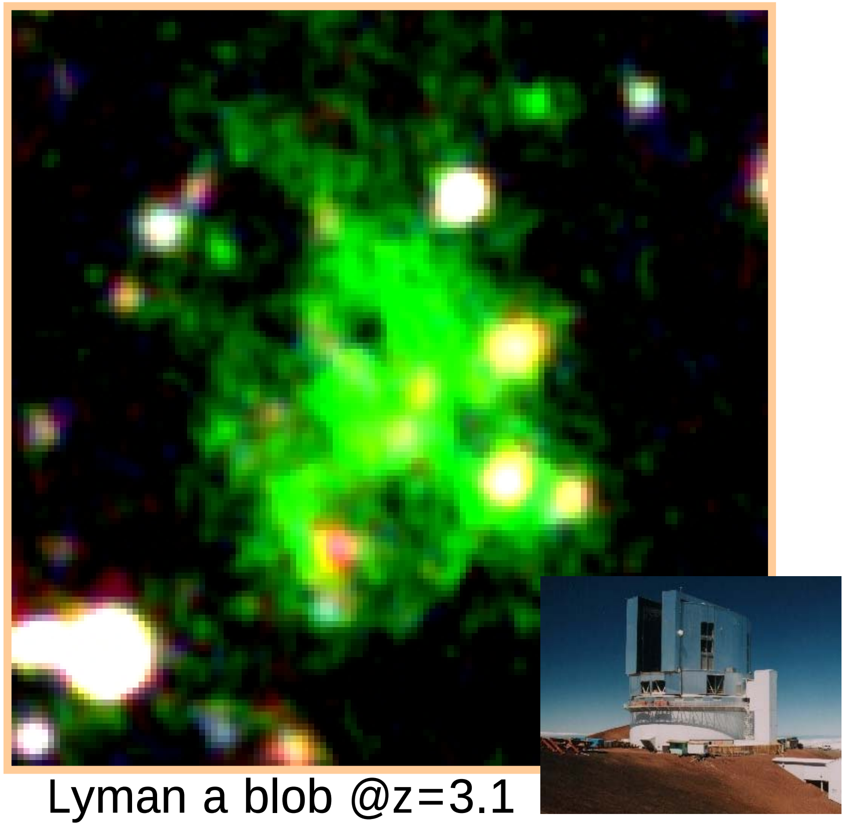
Hα (λ_0=656.3nm) enters mid-IR
at 5.25μm (z=7), 8.53μm (z=12)
Emitter Search for z>7?
Star-formation Rate? Dust Extinction (with Hβ)?



MIRACLE's FoV 6'x6'

- **Multi-slit + wide-field MIR imager**

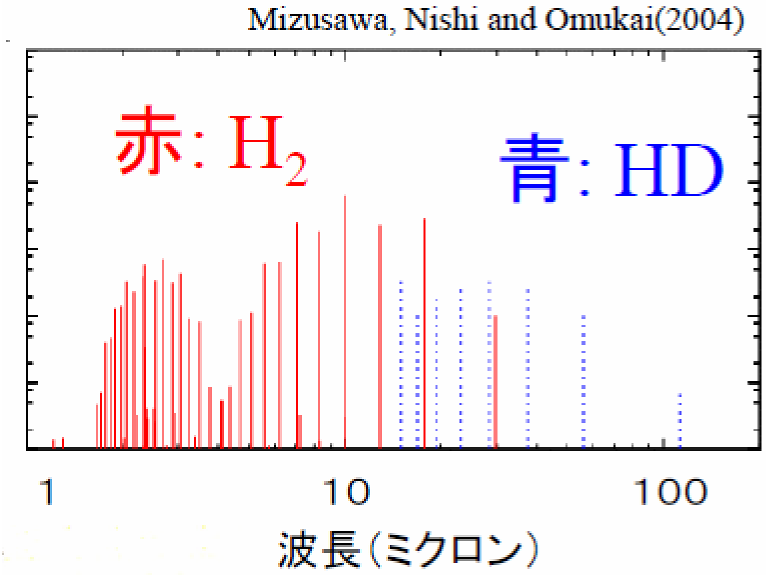
25" = 150 kpc

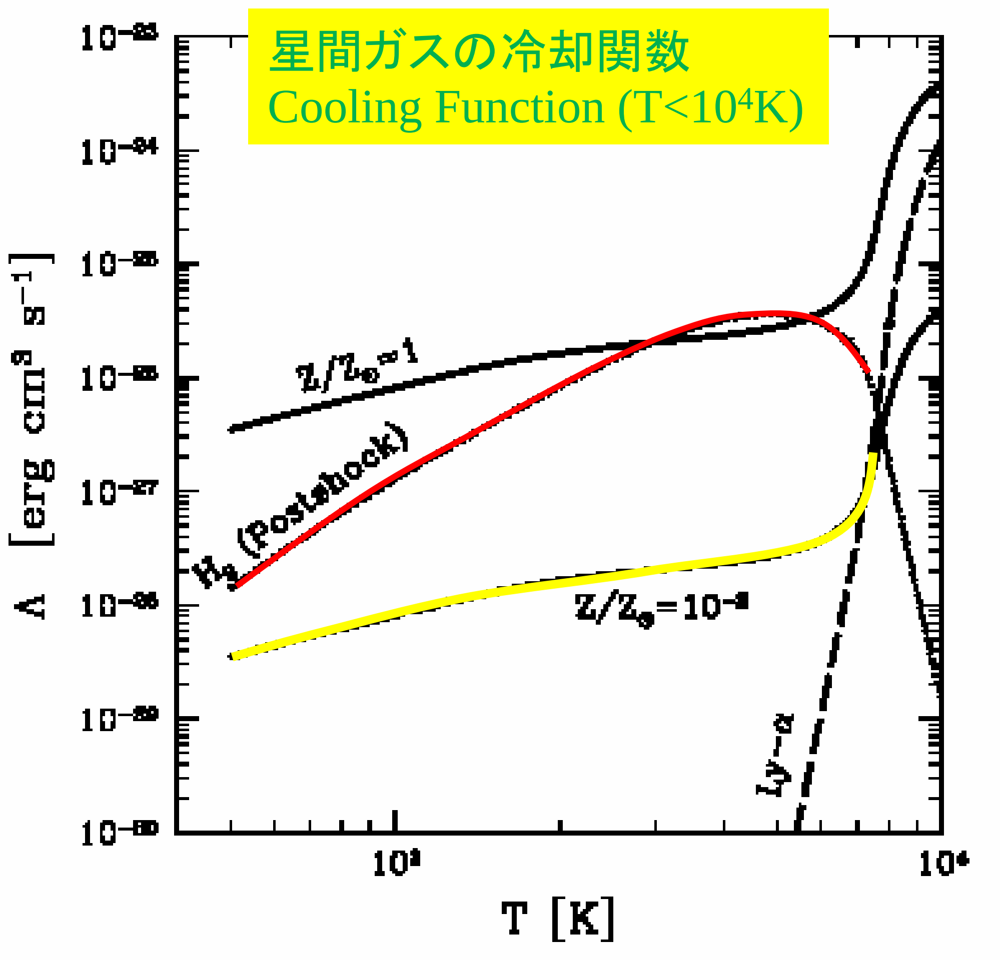


Lyman a blob @z=3.1
SSA22 "Blob1" (Steidel et al. 2000, Matsuda et al. 2004)

第一世代星の誕生を水素分子(H_2)輝線でとらえる

Probing the 1st stars with H_2 Emission Lines





元素合成が進んでいない宇宙初期の原始ガス(<$0.1Z_{sun}$) は

・H Lyα (T>10^4K)

・H_2 rotation lines 回転線(T<10^4K)で冷却する

これらのラインの観測が原始ガスの物理状態の理解に最も重要

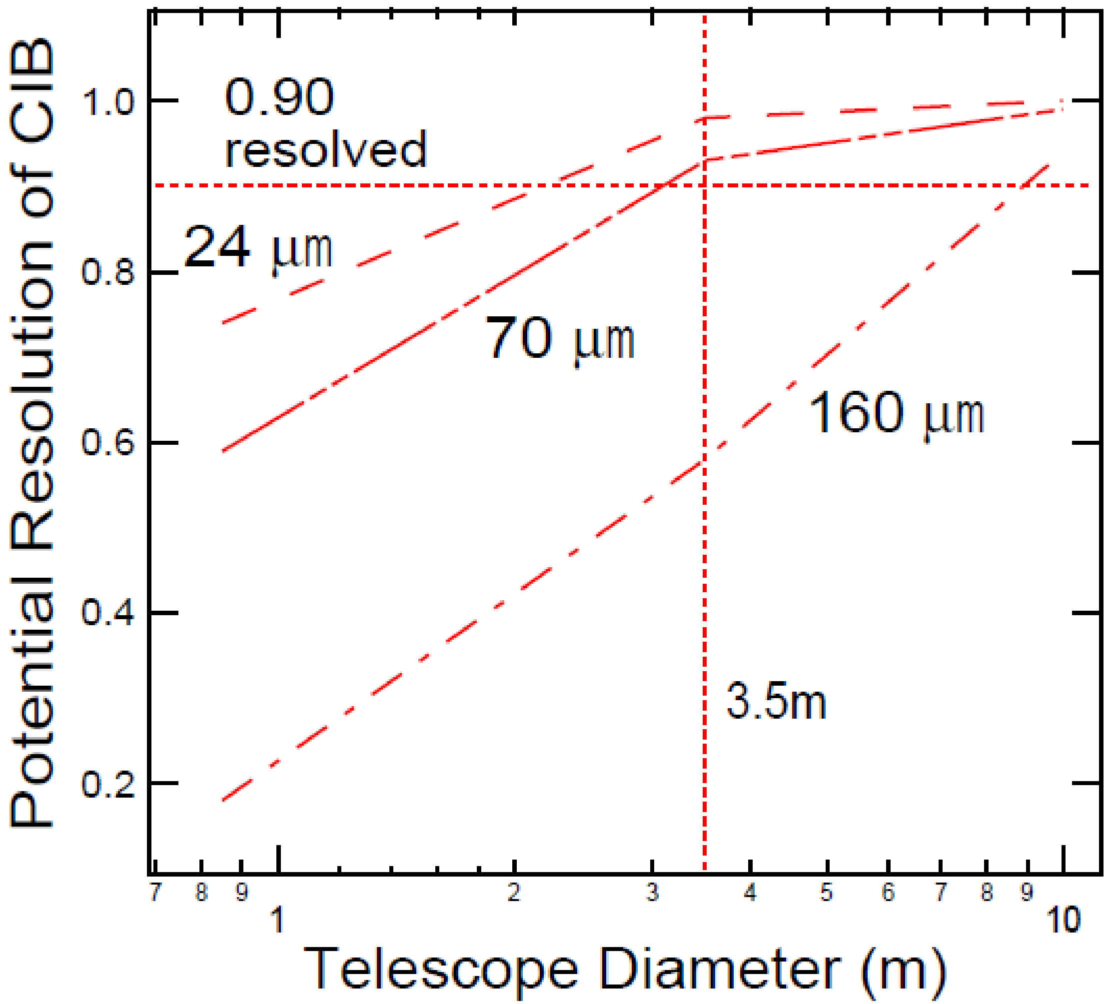
Most important lines to understand physics of metal-poor gas in the early universe

Extragalactic Science ：Objective #2

- 科学目的 Objective
  - 宇宙遠赤外線背景放射の大部分を個別天体に分解するとともに、遠赤外線背景放射の空間揺らぎの起源を明らかにする。
  - We will resolve the cosmic far-infrared background light into individual objects, and reveal the origin of the cosmic far-infrared background fluctuations.
- 科学目標 Target
  - 宇宙遠赤外線背景放射を、「あかり」の3倍以上の空間分解能により個別の遠赤外線天体に分解する。さらに個別天体を取り除いた遠赤外線背景放射ゆらぎを評価し、多波長相関解析等からその起源を解明する。
  - We will resolve the cosmic far-infrared background light into individual far-infrared objects with 3 times or more higher spatial resolution than that of AKARI. We then evaluate far-infrared background fluctuations after removal of the individual objects, and reveal its origin through detailed analysis such as multi-wavelength correlation.

中間赤外線撮像・低分散分光装置　MIRACLE
遠赤外線撮像分光装置 SAFARI　遠赤外線分光装置 BLISS

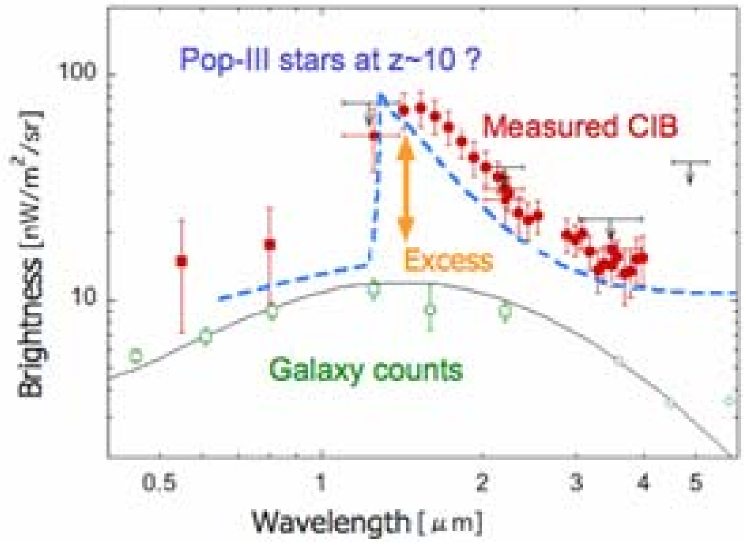
Resolving capability of the Cosmic Infrared Background (CIB)

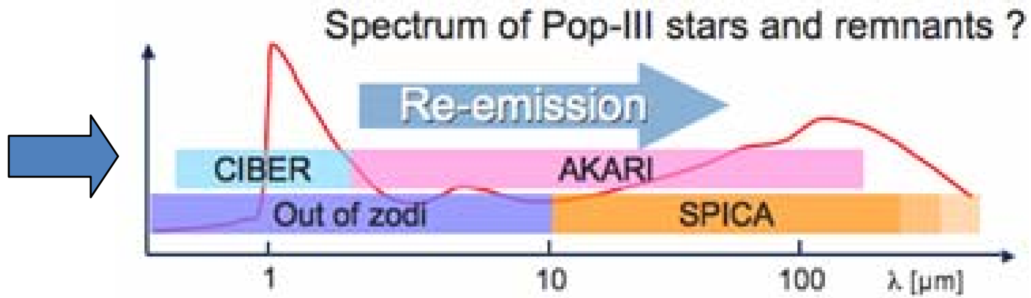


With an ideal point-source sensitivity limited by source confusion as a function of telescope diameter
(Dole et al. 2004)

The near-infrared background *(IRTS, COBE & AKARI)*

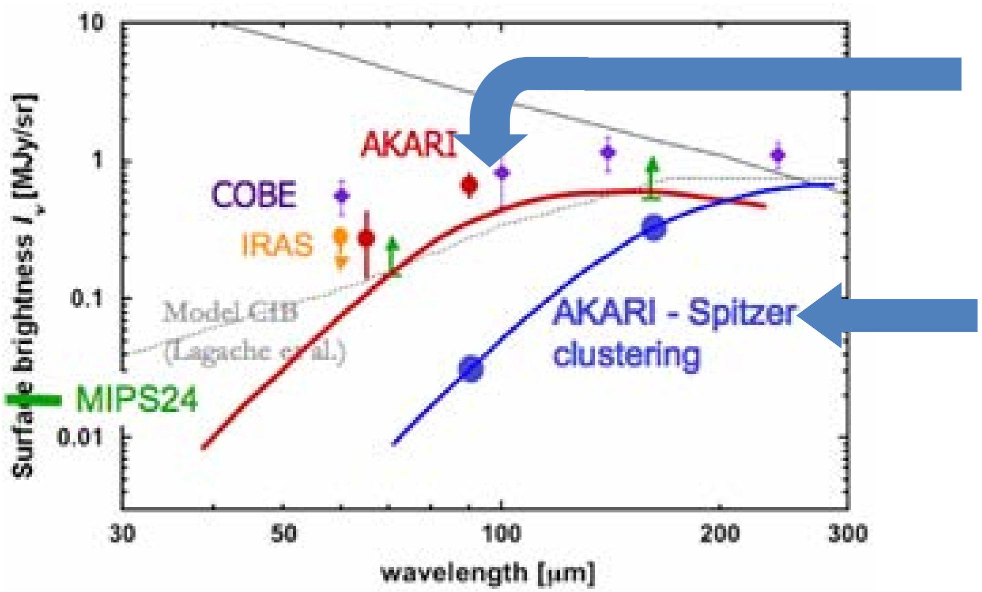
- *Proto-galaxies (e.g. pop-III stars, mini-quasars) at z~10?*





If substantial fraction of the energy of the NIR background is converted to dust emissions (IGM dusts, mini-quasars(AGN), etc.), it may form the far-infrared background.

The far-infrared background measurement with SPICA



AKARI found :

1) Excess brightness around 100um
   Corresponding to
   >10^10 gals/sr for S<100 uJy
   Proto-galaxies?
2) Large-scale fluctuations at 10'-30'
   ~5% of the mean CIRB level
   Very red foreground galaxies?

(Matsuura et al. 2009)

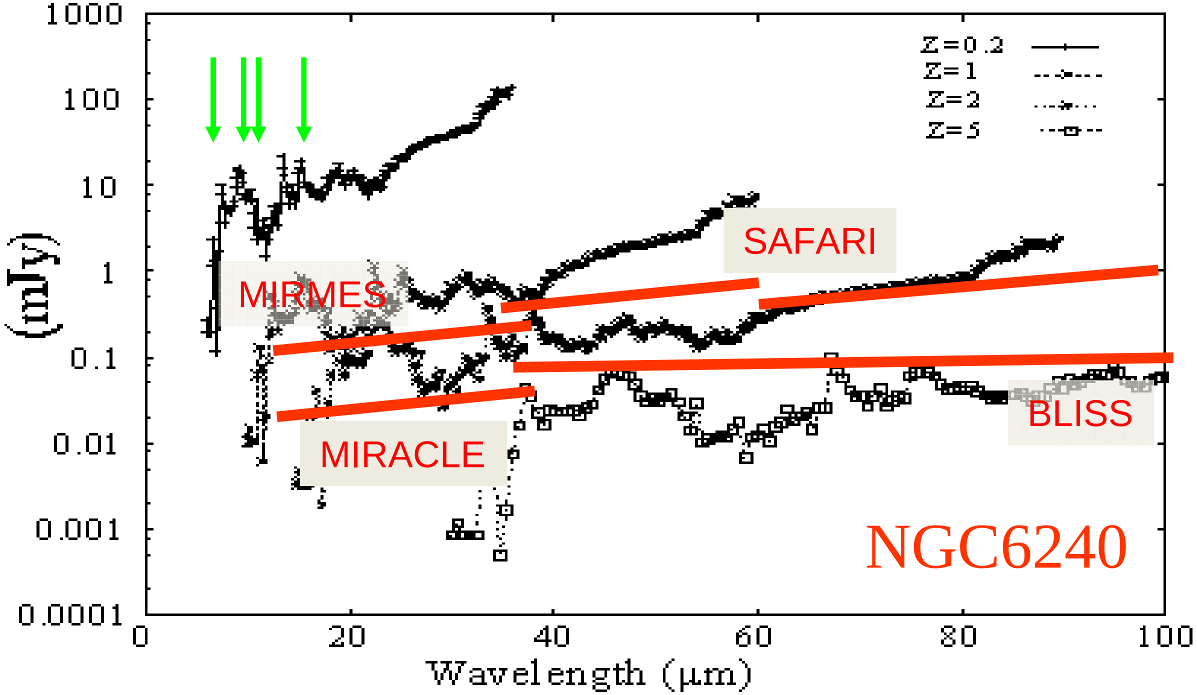
Extragalactic Science ：Objective #3

- 科学目的 Objective
  - 星間塵の影響を正しく評価し補正したうえで、星間環境の診断とダスト放射の理解を基に、塵に覆われた遠方銀河の物理化学を解明する。
  - We will reveal physical & chemical condition of high-z galaxies with precise correction for dust attenuation, based on understanding of interstellar environment and dust emission.
- 科学目標 Target
  - 赤方偏移3までの銀河について、中間・遠赤外線中分散広帯域分光観測を行ない、PAH放射や原子の電離輝線・分子輝線を効率的に捕らえ、その銀河の星間環境と星間ダストの性質を明らかにする。これにより、他波長のように星間塵の吸収補正の不定性なく、初期の宇宙（90億年前まで）の銀河の物理化学状態を明らかにする。
  - We will reveal interstellar environment and dust emission characteristics of high-redshift galaxies out to z~3 through PAH emission as well as atomic and molecular emission lines with broad-band mid- & far-IR moderate resolution spectroscopy. These observations allow us to reveal the physical & chemical conditions of dusty galaxies in the early universe (up to 9 Gyr ago) with precise correction for dust attenuation.

中間赤外線中分散分光装置　MIRMES　中間赤外線撮像装置　MIRACLE
遠赤外線撮像分光装置 SAFARI　遠赤外線分光装置 BLISS

Interstellar dust in distant galaxies

UIR band spectra at z=0.2, 1, 2, 5



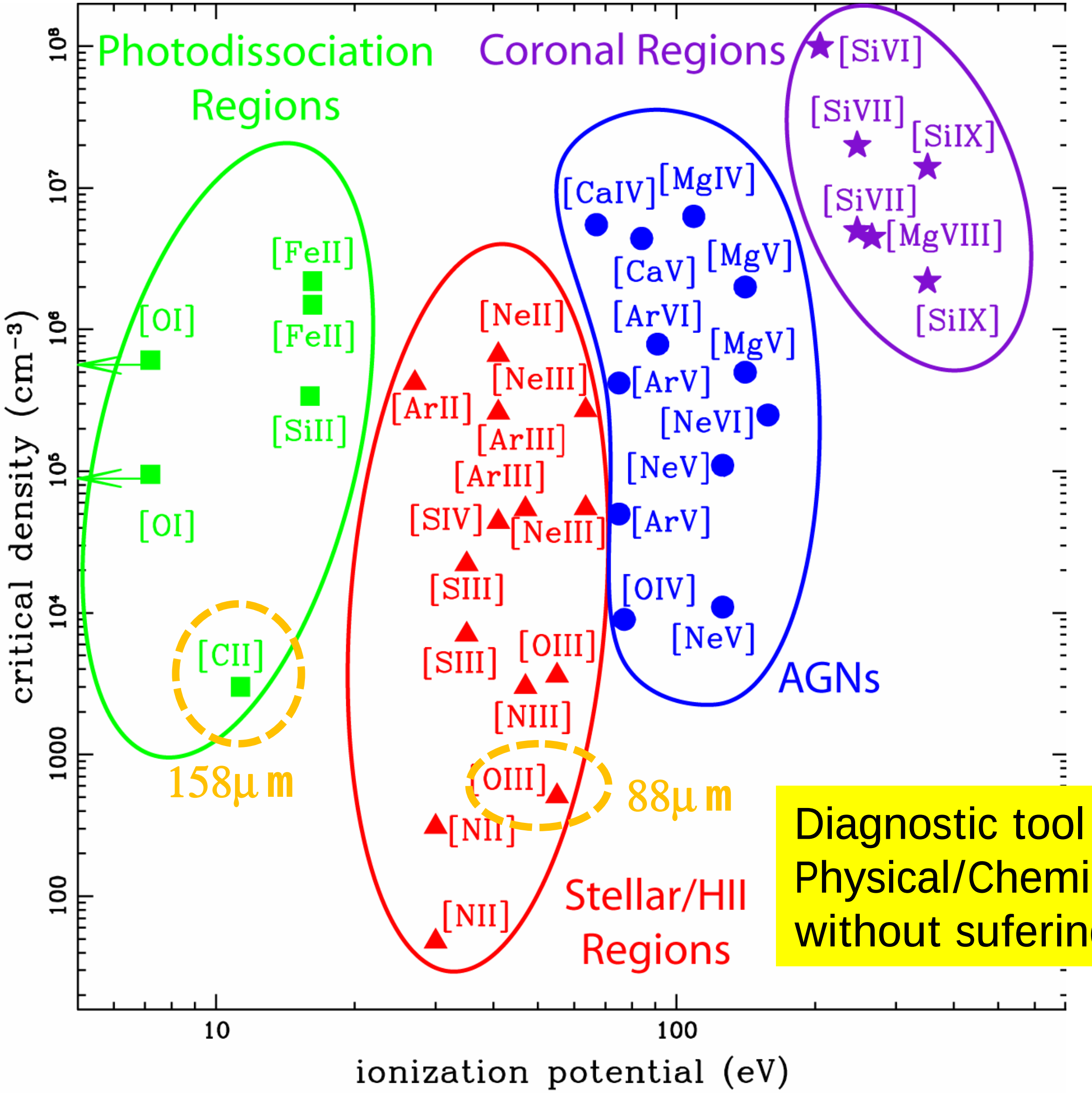
Moderate resolution Spectroscopy with SPICA (1hr, 5sigma)

MIRACLE R~50
MIRMES R~700
SAFARI $\Delta\sigma$=1cm-1,

Spectroscopic Diagnostics of Interstellar gas & dust out to z~3!

UIR band features at 3.3, 6.2, 7.6-7.8, 8.6, 11.2, 12.7μm
atomic ionic lines; [ArIII] at 8.99μm (27.63eV, $n^{c}_{e}=4.8\cdot10^{5}$)
[SIV] at 10.51μm (34.83eV, $n^{c}_{e}=5.6\cdot10^{4}$)
[NeII] at 12.81μm (21.56eV, $n^{c}_{e}=5.4\cdot10^{5}$)

Numerous Atomic/Ionic Fine-structure Lines exist in the Mid- to Far-infrared



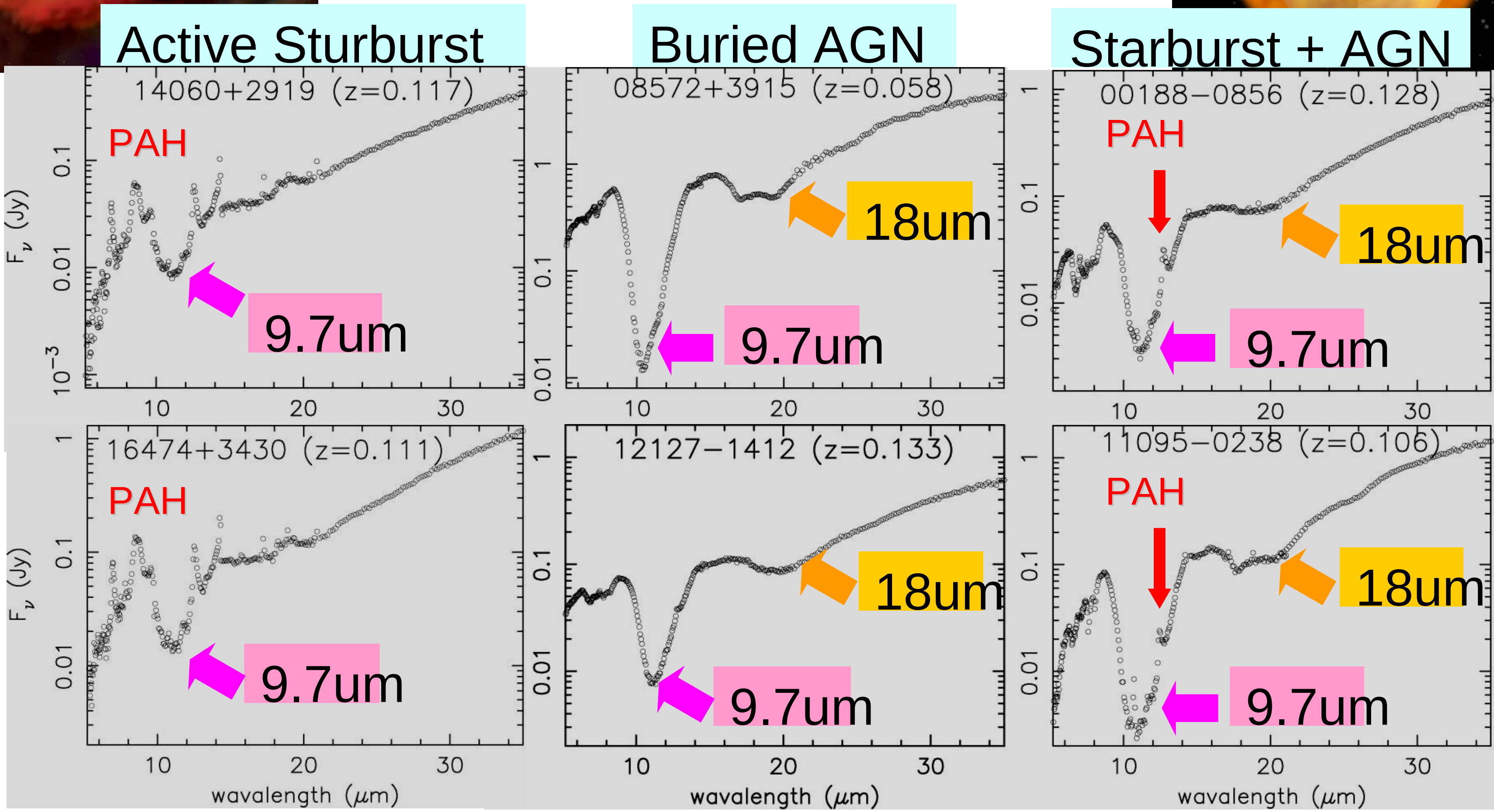
Diagnostic tool to study the Physical/Chemical Condition without sufering from dust extinction

Extragalactic Science ：Objective #4

- 科学目的　Objective
  - 銀河の進化における超巨大ブラックホール※の役割を解明するため、他の手法では観測が困難な星間塵に囲まれた形成中の超巨大ブラックホールを、初期宇宙にいたるまで探査する。
    ※太陽の数億個に相当する質量があると思われるブラックホール
  - In order to understand the role of supper-massive black holes (SMBHs) in the galaxy evolution, we will make a survey for the forming SMBHs, that may not be observed easily in other methods due to the obscuration by dust, from the present to the early universe.
- 科学目標　Target
  - 星間塵の影響を受けない赤外線撮像・分光観測により、他の手法では観測が困難な星間塵に囲まれた形成中の超巨大ブラックホールを、現在の宇宙から初期宇宙に至るまで広く探査し、TBD個のサンプルを構築する。これと、銀河形成史の観測結果とをくみあわせて、銀河の進化における超巨大ブラックホールの役割を解明する。
  - We will make infrared imaging & spectroscopic observations of TBD number of the forming super-massive black holes (SMBHs), that can not be observed easily in other methods due to the obscuration of dust, from the present to the early universe. Supplementing these results with the results of observations for the galaxy formation history, we will understand the role of SMBHs in the galaxy evolution.

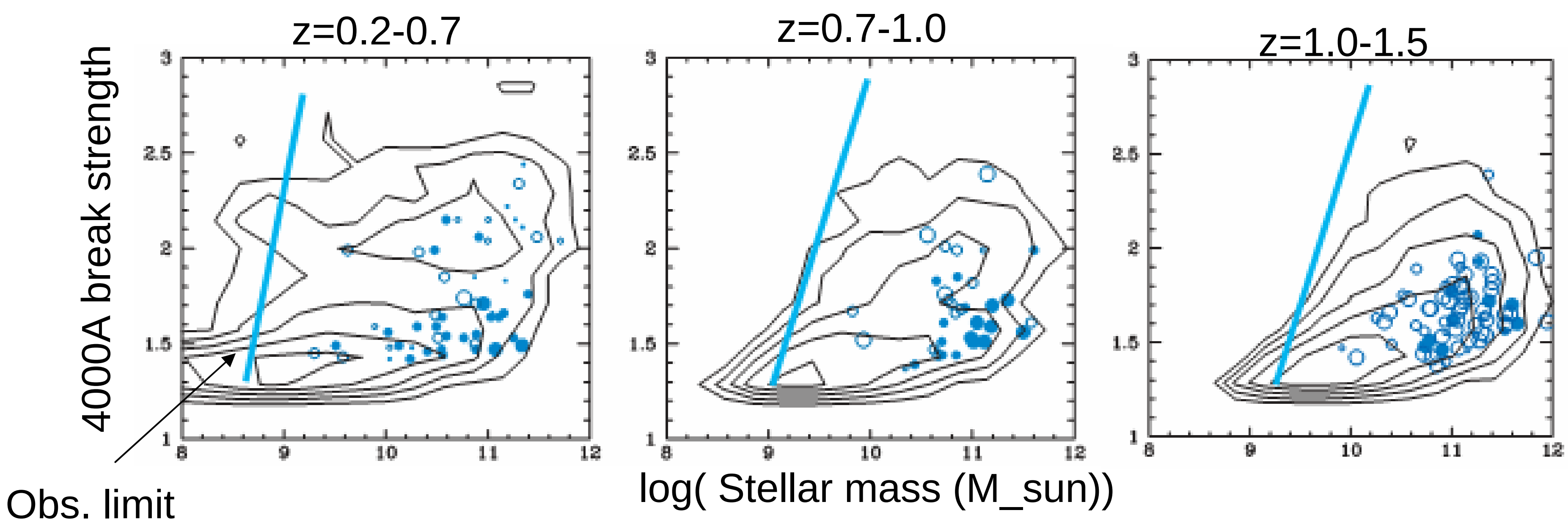
中間赤外線撮像・低分散分光装置　MIRACLE
中間赤外線中分散分光装置 MIRMES　**遠赤外線撮像分光装置 SAFARI**

5-35 μm spectra of ULIRGs



With Spitzer & AKARI, only 24 micron-very-bright ULIRGs (biased sample) could be studied at z > 1: SPICA enables us to go to z > 3 and to general ULIRGs at z > 1 !!

Evolution of galaxies and the growth of supper massive blackholes



Contours : the galaxy distribution in SXDF
Blue filled (spec-z) and open (phot-z) circles : X-ray sources (AGN)

At z=1.0-1.5, AGN are associated with massive star-forming galaxies, while at z=0.2-0.7, the AGN number associated with massive red galaxies increases.

→Do some X-ray AGN follow the track from star-forming to red, passive galaxies (and their activities are going to turn off)? How about dusty obscured AGN?.

→ SPICA/SAFARI low-resolution spectrophotometric imaging survey over ~100 sq. deg!!

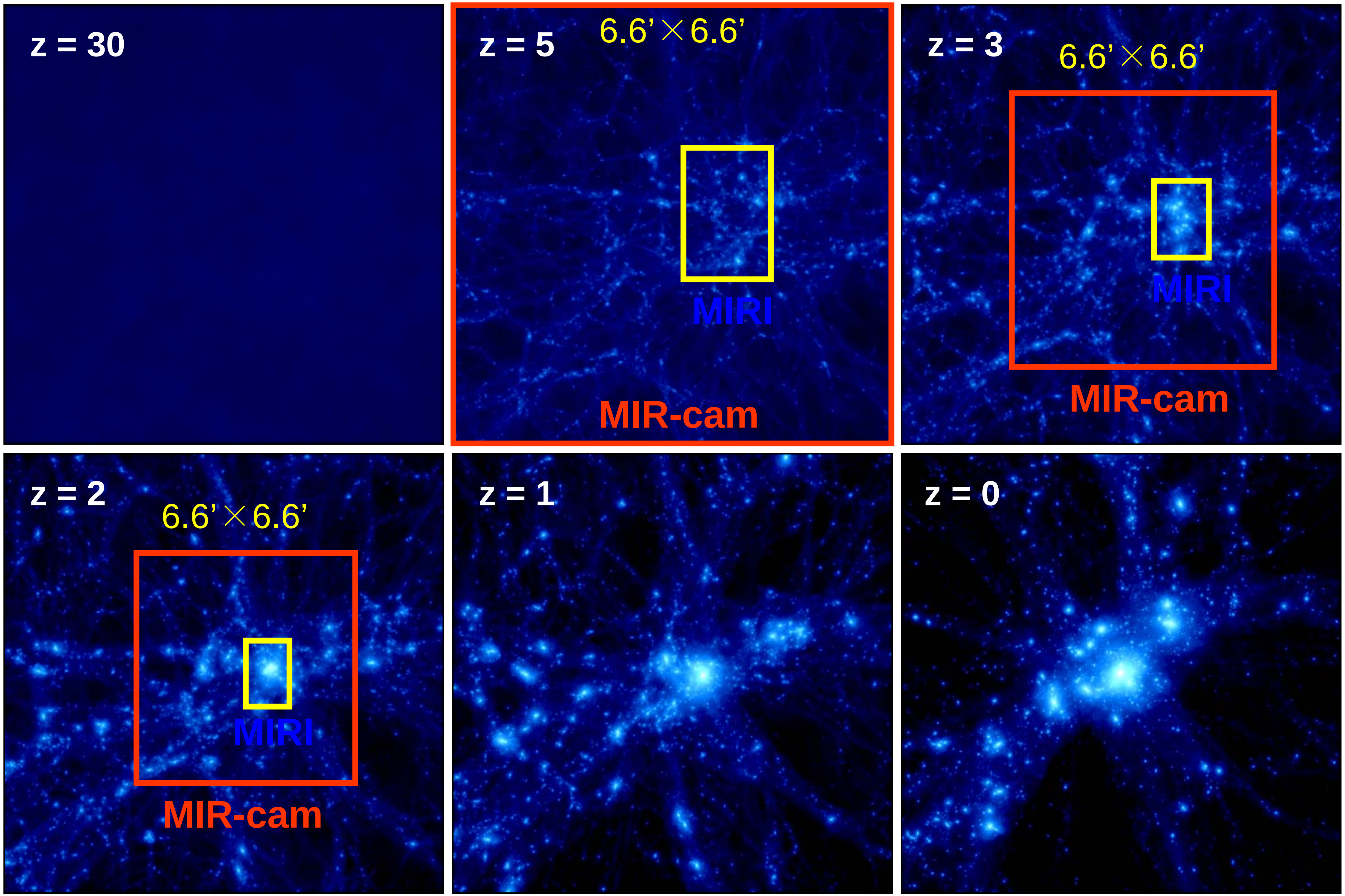
Subaru XMM deep survey field (SXDS) (Akiyama et al.天文月報2008年1月号)

Extragalactic Science：Objective #5

- 科学目的 Objective
  - 銀河の星形成史・質量集積史を、銀河団や大規模構造の形成過程と銀河進化への影響との関わりの中で、解明する。
  - We will reveal the star-formation & mass assembly history of galaxies in relation to the forming processes of the galaxy clusters and the large scale structures, as well as the environmental effect on the galaxy evolution.
- 科学目標 Target
  - 星形成活動のピーク(70－100億年前、z=1~2)があったとされる時代の宇宙において、放射エネルギーが赤方偏移してきた赤外線領域で、大規模構造をトレースできるほどの広い天域（~300メガパーセク相当)をサーベイし、銀河団や大規模構造を観測する。これにより、宇宙星形成史・質量集積史および銀河進化に対する環境効果を解明する。
  - In the early universe where the star forming activities was at a peak, we will undertake imaging wide-area survey and observe the galaxy clusters and the large scale structures at infrared wavelength, to which the redshifted emitting energy shifts. The large survey area (corresponding to ~300 Mpc) can trace the large scale structures, and we will reveal the star formation history in the early universe (up to 9 Gyr ago) as well as the mass assembly history and its environmental effect on the galaxy evolution.

中間赤外線撮像装置 MIRACLE 遠赤外線撮像装置 SAFARI

SPICA MIR-cam (JWST MIRIの20倍)で探る宇宙の質量集積史

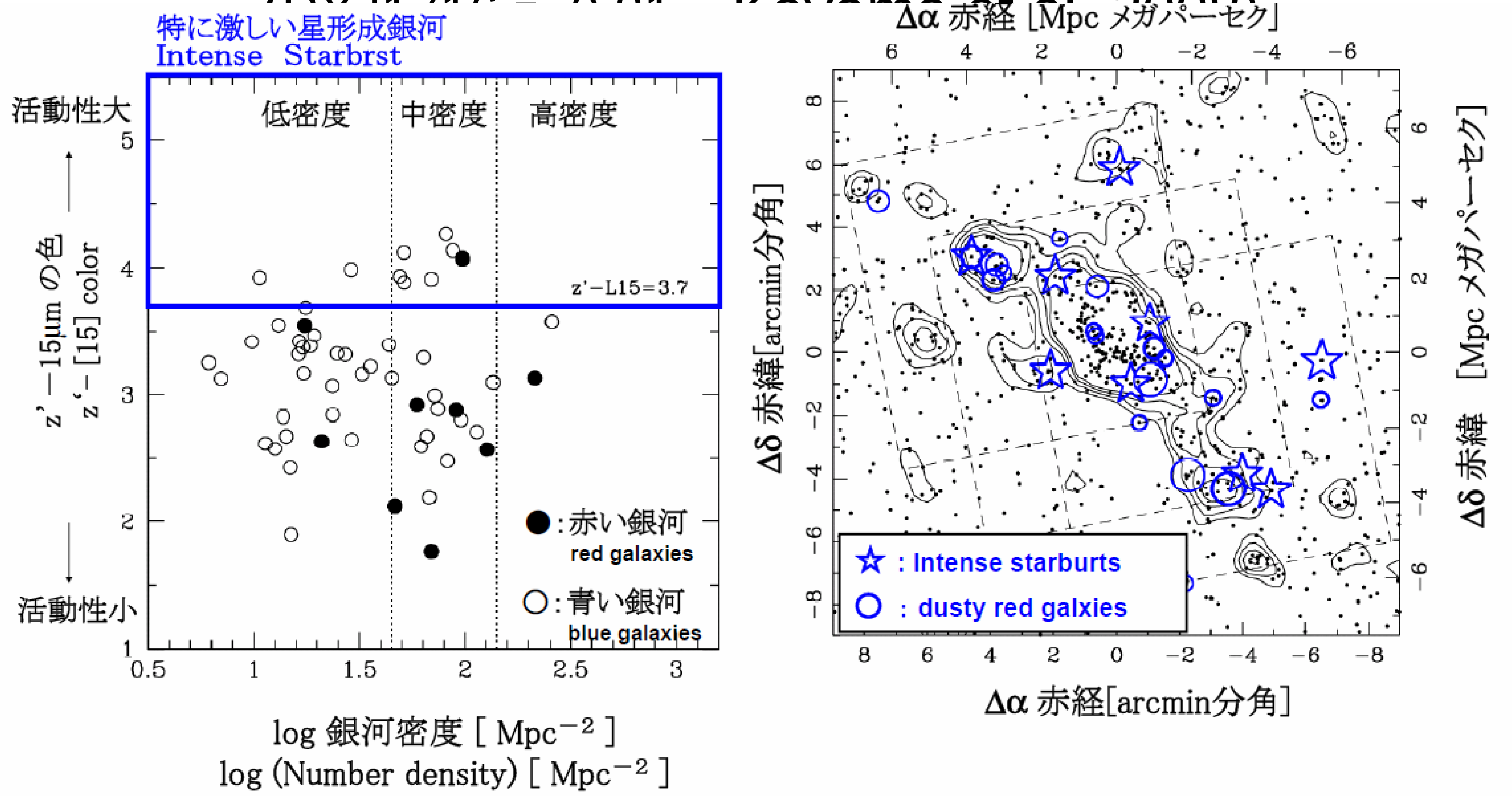


A Massive Cluster (6×10^{14} M$_\odot$), 20×20Mpc^2 (co-moving)

Yahagi et al. (2005)

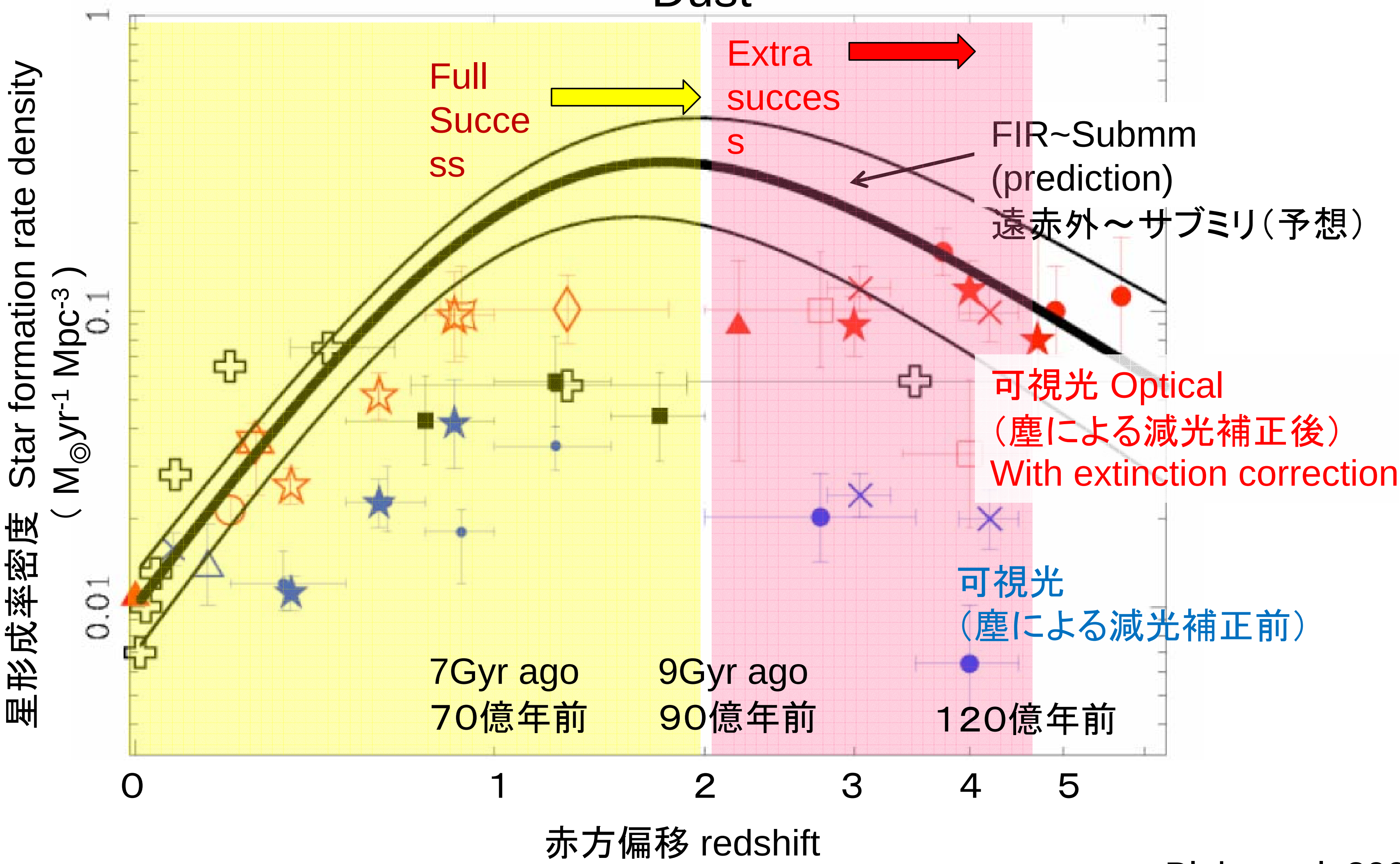
Environmental Effect in distant Cluster revealed with AKARI & Subaru

(RXJ1716 z = 0.81, Koyama et al. 2008)



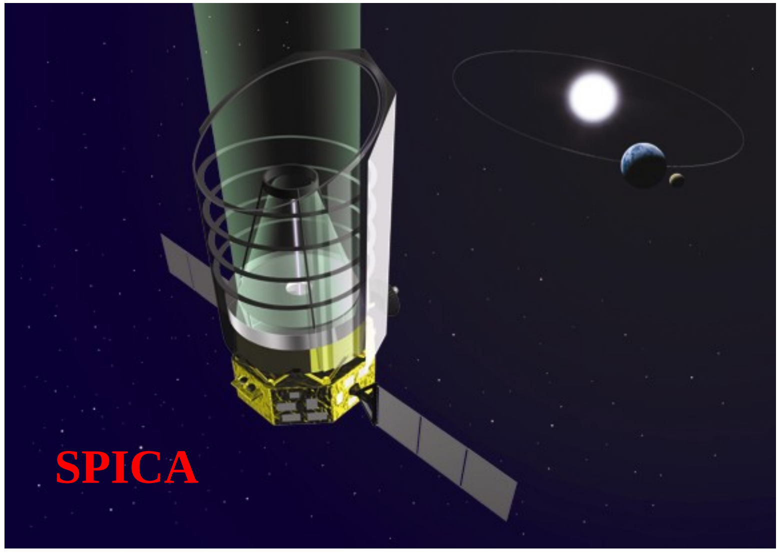
塵に覆われた宇宙の星形成史の解明

Understanding the Cosmic Star-Formation History Obscured by Dust



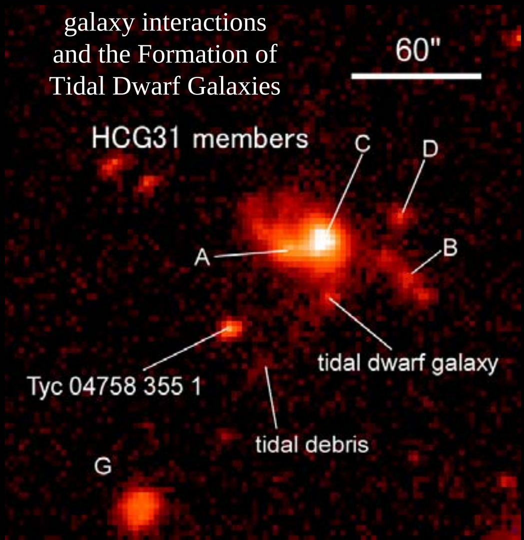
Blain et al. 2002

Major Objective [2]
銀河星間空間における
物質輪廻の解明
The Transmigration of Dust in the Universe

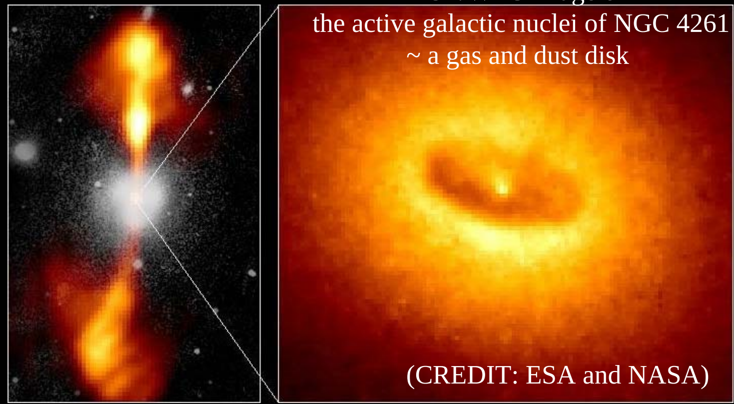


Life Cycle of Dust

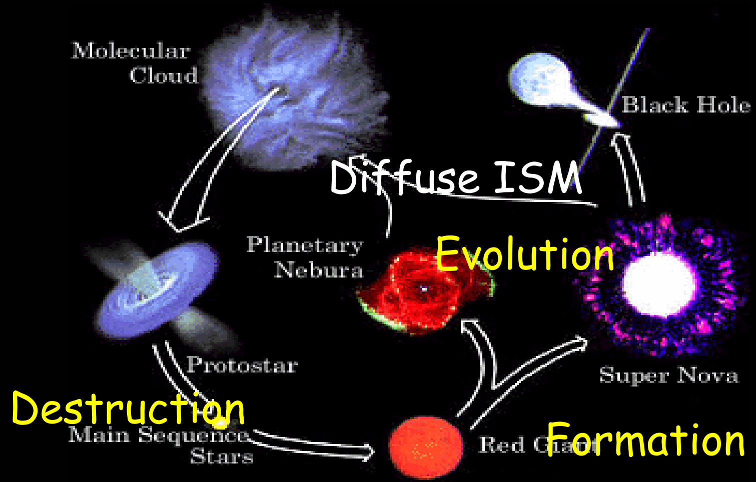
AKARI 9μm image of
Hickson Compact Group 31
~ the site of
galaxy interactions
and the Formation of
Tidal Dwarf Galaxies



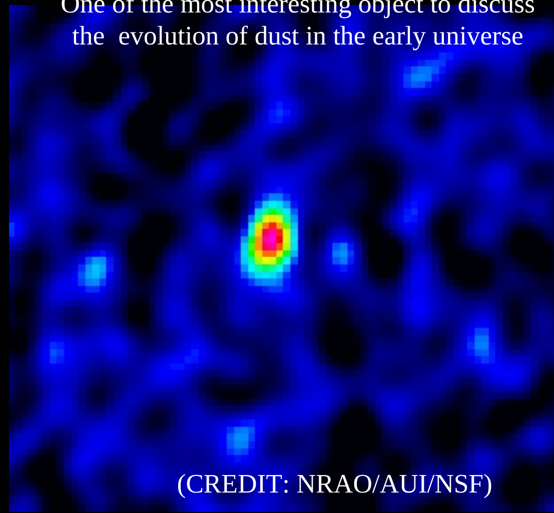
HST/WFC image of
the active galactic nuclei of NGC 4261
~ a gas and dust disk



(CREDIT: ESA and NASA)



VLA image of J1148+5251
~the most distant quasar at z~6.4
One of the most interesting object to discuss
the evolution of dust in the early universe



(CREDIT: NRAO/AUI/NSF)

-- where the dust is formed
-- how they are ejected into the interstellar space
-- how they evolve in the interstellar space in a galaxy
-- where and how the dust is destroyed
-- how they enrich the universe

Life Cycle of dust：Objective #1

- 科学目的 Objective
  - 大質量星終焉のダスト形成過程を解明し、初期宇宙のダスト起源を探る。
  - The dust formation scenarios by massive stars are examined to explore the origin of interstellar dust in the early universe.
- 科学目標 Target
  - 25Mpc以内の近傍銀河内で起こるダスト形成の兆候が見られる超新星(~5個以上)について、爆発後から1～2年間に複数回のデータ取得を行う。これにより、超新星放出ガスからダストが新たに凝縮する過程、また、それらが既存の星周ダストの温度(数百度K)に冷える過程の中間赤外スペクトル変化を調べ、超新星ejecta中で形成されるダストの組成、サイズ分布、質量を詳細に制限する。
  - Observations of several (>~5) dust-forming supernovae in nearby (<25Mpc) galaxies are required several times within 1-2 years after the explosion. Changings in mid-infrared spectra of the supernova during the processes in which the dust is newly condensed in the SN ejecta gas and then it is cooled down to the temperature of circumstellar pre-existing dust (~ a few hundred K) are examined to specify its composition, its size distribution and its total mass.

中間赤外線低分散分光装置 MIRACLE　中分散分光装置　MIRMES
遠赤外線分光撮像装置 SAFARI

Dust formation process by massive stars

SCIENTIFIC BACKGROUND

- 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)

    -> $4\times10^{-5}M_{solar}$ (Meikle et al. 2007)
  - Type II SN1987A ; $7.5\times10^{-4}M_{solar}$ (Ercolano et al.2007)
  - Cas A ; $0.003M_{solar}$ (Hines et al. 2004) or 0.02-$0.054M_{solar}$ (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)

ISSUES TO BE SOLVED

-- Dust formation mechanisms in the SN ejecta

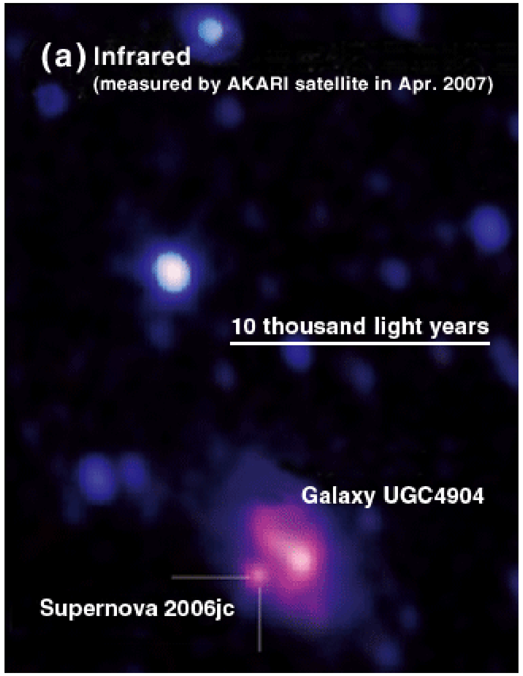
- Processes of transitions among SN ejecta gas, precursor molecules and SN dust
- Geometry of the newly condensed dust; newly formed dust forms in clumpy structures?

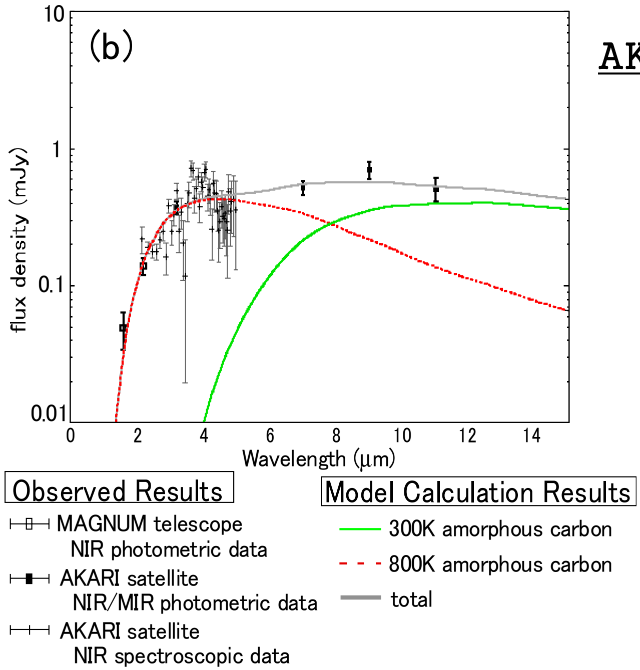
-- Relation between the SN types and dust formation.

- Differences in compositions and size distributions of newly condensed dust in the SN ejecta.
- How much fraction of dust formed in SN ejecta can survive to become the interstellar dust.

Dust formation process by massive stars

Example of the Latest Results on the Dust Formation by Core-collapse SNe





<u>AKARI/IRC observations of SN2006jc</u>

(a) Three false-colors composite image of the SN2006jc on epoch 220 days and the host galaxy UGC4904 taken with AKARI/IRC [3μm(blue), 7μm(green) & 11μm(red)]

(b) Near- to mid-infrared spectral energy distribution of SN2006jc on epoch 220 days. The gray solid line shows the result of model calculation for dust thermal radiation. This reveals that 300K amorphous carbon dust (green solid line) exists in addition to 800K amorphous carbon dust (red dotted line). (see Sakon et al. 2009)

→ 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 (Sakon et al. 2009).

Excellent sensitivity (>10 times better than AKARI/IRC) and wider wavelength coverage in the mid-infrared (5-40μm) achieved by MIRACLE low-resolution spectroscopy enable us to detect $10^{-5}M_{\odot}$ of dust which is cooled down to a few hundred Kelvin even at the distance of 25Mpc.

→ providing strong constraints on the composition and the mass of newly formed dust in the ejecta of various types of SNe in nearby galaxies

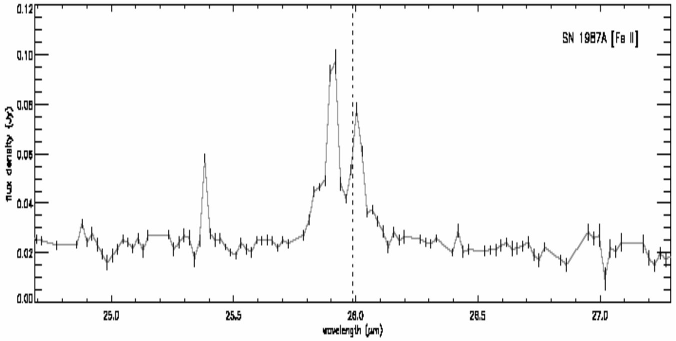
Dust formation process by massive stars

Understanding transitions among the SNe ejecta gas, precursory molecules and Newly Formed Dust

IR lines including a population of silicate particle *

[FIV] 25.83µm
[OIV] * 25.89µm
[FeII] * 25.99µm
[SiII] * 34.82µm

[NeII] 12.8µm
[NeIII] 15.5µm
[OIII] 51.8µm
[NIII] 57.3µm
[PII] 60.6µm
[OI] 63.2µm
[OIII] 88.4µm
[NII] 121.9µm
[CII] 157.7µm
[OI] 145.5µm
(from Reach et al. 2000)



Spitzer LH spectrum of SN1987A around the [FeII] 25.99µm line. [OIV] 25.89µm and [FeII] 25.99µm are not well resolved due to the contribution of [FIV] 25.83µm. (Bouchet et al. 2006)

→ *R>1000 is required to decompose the lines of [FIV], [OIV] and [FeII]*

Important molecules formed in the ejecta

SiO (8.1~8.6µm; $^{28}Si^{16}O$ 1-0)
Precursor of silicate dust ($MgSiO_3$, Mg_2SiO_4 and SiO_2)
(Schneider et al. 2004)

CO (4.74µm 1-0 P(8))
C is bounded in CO if C<O
(Clayton et al. 1999)

[FeII], [SiII] ;
Vaporization of pre-existing silicate dust is indicated

[OIII] / [OI] ; the density and temperature of the emitting region is constrained

High-dispersion (R>1000) spectroscopic abilities in the mid- infrared (10-36µm) with MIRMES and in the far-infrared (35-200µm) with SAFARI is indispensable for demonstrating the transitions from the SN ejecta gas to the SN dust.

Life Cycle of dust：Objective #2

- 科学目的 Objective
  - 中・小質量星によるダスト形成過程を解明し、天の川銀河中のダスト、即ち現在の宇宙のダストの起源における中小質量星の役割を探る。
  - The dust formation processes by low- to intermediate-mass stars are examined to explore the origin of dust in the Milky Way and, thus, in the current universe.
- 科学目標 Target
  - 系内、及びマゼラン雲中のAGB星、惑星状星雲、新星など進化した中小質量星約30個の星周の希薄なダストシェルを空間分解し、撮像情報から過去の質量放出とダスト形成の歴史を調べる。また星周の分子・ダストシェルの中間赤外~遠赤外分光データから、分子・ダストシェルの組成を調べ、放出ガスから形成されたダストの性質を制限する。
  - Spatially well-resolved observations of faint dust shells around ~30 low- to intermediate-mass evolved stars (e.g., AGB stars, planetary nebulae, novae etc) in the Milky Way and in the Magellanic clouds are required to investigate their mass-loss histories and the dust-formation processes. Mid- to far-infrared spectra of spatially-resolved molecular and dust shell are obtained to identify the constituents of the molecular/dust shells and the properties of dust formed in the mass-loss gas.

中間赤外線撮像装置 MIRACLE　**中分散分光装置 MIRMES**
中間赤外線高分散分光装置 HIRES　**遠赤外線分光撮像装置 SAFARI**

Dust formation process by low-to intermediate mass stars

SCIENTIFIC BACKGROUND
Chemical evolution models for dust budgets in the Milky Way (Dwek 1998)
Silicate dust; Type II SNe, red supergiants, O-rich AGB stars
Carbonaceous dust; mainly in low-mass (2-5$M_{\odot}$) C-rich AGB star
Metalic iron; Type Ia SNe

Observations (Waters 2004; Cohen & Barkiw 2005)

Asymptotic Giant Branch (AGB) stars with C/O<1 in their envelope
・・・presense of several silicate dust species
Asymptotic Giant Branch (AGB) stars with C/O>1 in their envelope
・・・presense of amorphous carbon, SiC, MgS, and in some cases PAHs

PAH features in the mid-infrared appear after the AGB phase and are observed in C-rich Planetary Nebulae

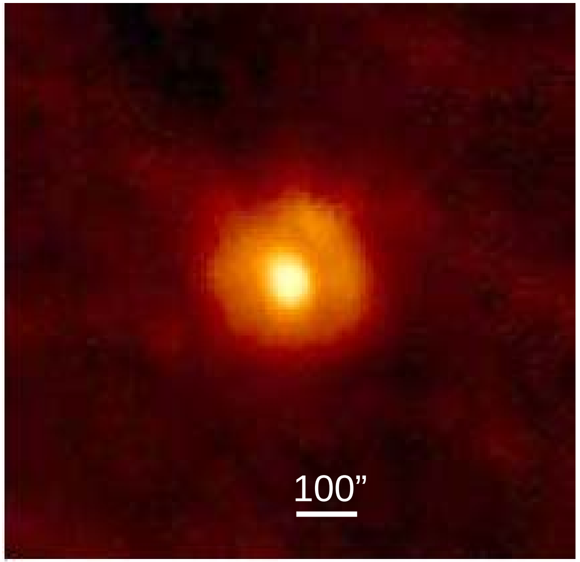
ISSUES TO BE SOLVED

-- Identifying some of the molecules in the MOLsphere (Tsuji 2000) of redgiants to explore the driving force of mass ejection and to understand the formation process of MOLsphere.

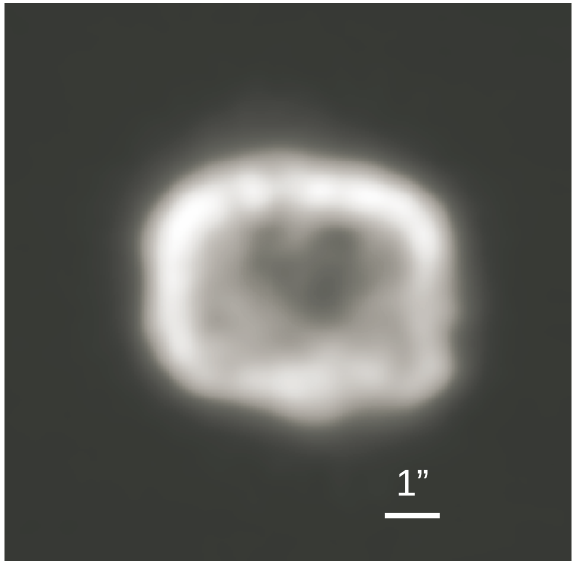
-- Demonstrating how the dust is formed around the AGB stars and how it is ejected into the ISM at the evolutionary end phase of the AGB stars

Dust formation process by low-to intermediate-mass stars

High spatial resolution (~0.37”) and excellent sensitivity in the mid-infrared (5-40μm) achieved by MIRACLE multi-band imaging enable us to examine the detailed structure of the circumstellar dust shells around the evolved low- to intermediate-mass stars.



AKARI 90μm image of a famous red-giant U Hydra. The dust in the shell was formed about 10^4 years ago. (ISAS/JAXA)



Subaru COMICS 11.7μm image of Galactic planetary nebula BD30+3639. Image size is 10”.64 x 10”.64. (Matsumoto et al. 2008)

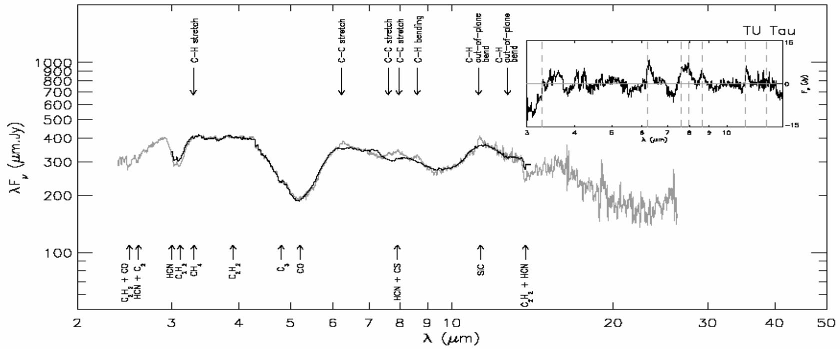
- Possible dust shell around the AGB stars are quite faint due to the deficiency of ultra-violet photons from the central star.
- Only a few bright PNe have ever been spatially resolved in the mid- to far-infrared using ground-based facilities.

→High spatial resolution and high sensitivity in the mid- to far-infrared with MIRACLE and SAFARI can demonstrate the dynamical and chemical process in which circumstellar dust is ejected into the inter-stellar space.

Dust formation process by low–to intermediate mass stars

UIR bands in the ISO SWS spectrum of carbon-rich AGB star TU Tauri (Boersma et al. 2006)

TU Tauri has, so far, been the only AGB star that is known to have PAHs; the presence of the UIR bands in TU Tau is attributed to UV photons originating from the A2 companion



Excellent sensitivity (>10 times of AKARI/IRC) and wide wavelength coverage in the mid-infrared (5-40μm) achieved by MIRACLE low-resolution spectroscopy are quite useful to detect the faint dust features dominantly powered by soft optical radiations in the circumstellar dust shells around the AGB stars.

→ Possible detection of PAHs features in the envelope of AGB stars, which should be the first direct observational evidence for the formation of PAHs in the AGB phase

High-dispersion (R>10000) spectroscopic abilities in the mid-infrared (4-20μm) with MIRHES is crucial to examine the properties of molecules in MOLsphere of redgiants.

Moderate-dispersion (R>600~1000) spectroscopic abilities in the mid-infrared (10-36μm) with MIRMES and in the far-infrared (35-200μm) with SAFARI is crucial to examine the physical conditions and chemical composition of the circumstellar gas, molecules and dust grains around the evolved low- to intermediate-mass stars.

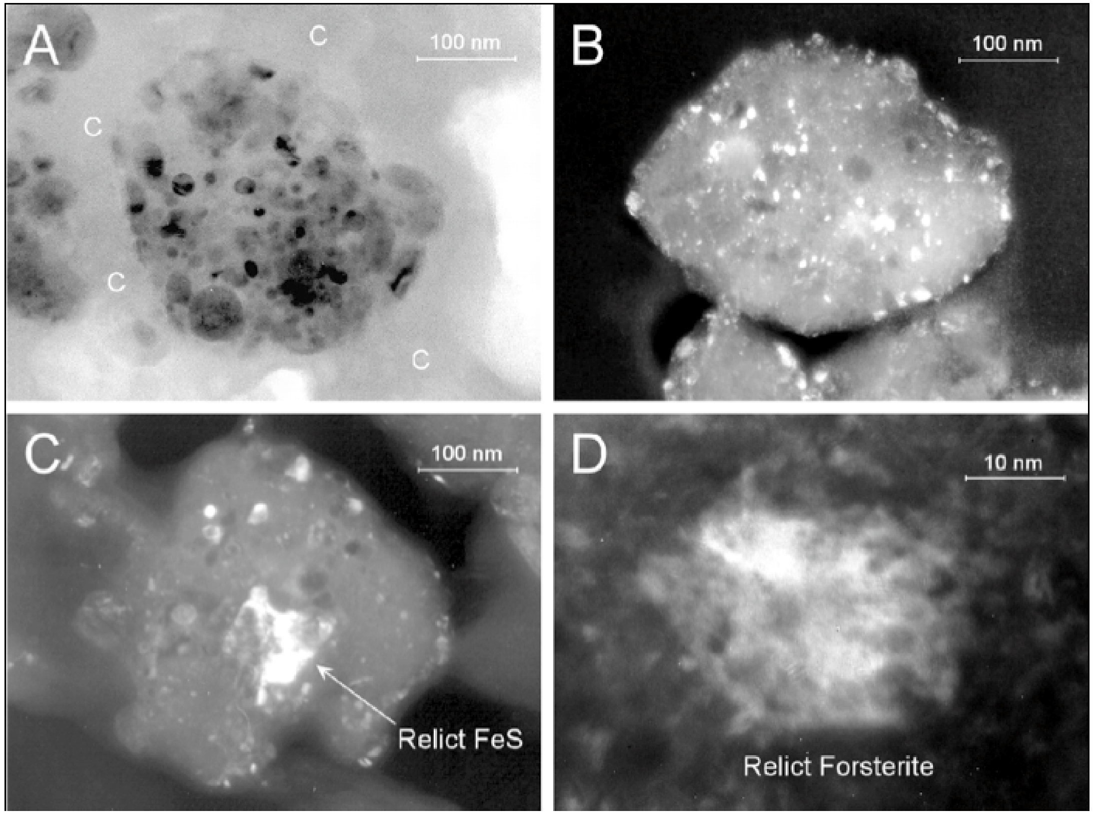
Life Cycle of dust：Objective #3

- 科学目的 Objective
  - 低温高密度分子雲中におけるダスト形成・成長の過程を探る。
  - Dust formation and grain growth in the cold dense molecular clouds are examined.
- 科学目標 Target
  - 系内の若い星を内包するcold dense molecular cloudsの中間~遠赤外分光観測によってiron sulphideの赤外バンドを検出し、Inter planetary Dust Particles (IDPs)中に見られるGlass with Embedded Metals and Sulfides (GEMS)とInterstellar dustの関連を解明する。これによって低温高密度分子雲中におけるダスト粒子の成長のシナリオを探る。
  - Mid- to Far-infrared spectroscopic observations of cold dense molecular clouds with embedded young stellar objects in the Milky Way are required to detect the infrared bands of iron sulphide grains and to demonstrate the link between the Glass with Embedded Metals and Sulfides (GEMS) in Interplanetary Dust Particles (IDPs) and the interstellar grains. Then the grain growth scenario in cold dense molecular clouds are explored.

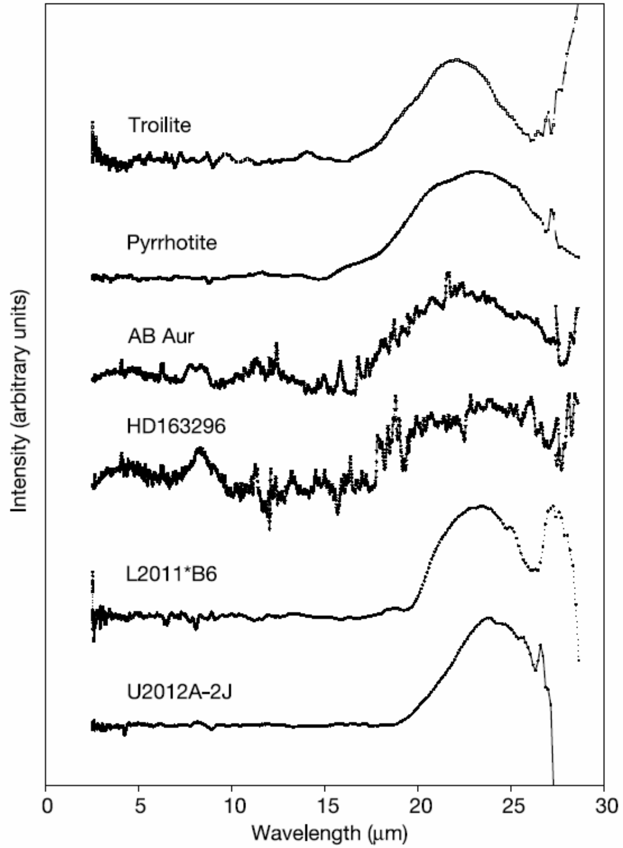
中分散分光装置 MIRMES　中間赤外線高分散分光装置 HIRES
遠赤外線分光撮像装置 SAFARI

Detection of iron sulphide grains in cold dense molecular clouds

A Linkage between the Glass with Embedded Metals and Sulfides (GEMS) in Interplanetary Dust Particles (IDPs) and the interstellar silicate grains



Glass with Embedded Metals and Sulfides (GEMS) in IDPs (Bradley et al. 1999)



Infrared spectra of troilite (FeS) and sulphide-rich IDPs compared to "23.5μm" feature in ISO SWS spectra of two young stars AB Aurigae, HD163296 after subtracting the model spectra composed of amorphous silicates, metallic Fe and carbonaceous materials and water ice.

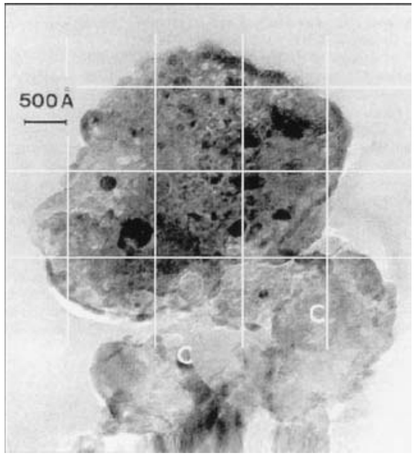
(Keller et al. 2002, Science, 417, 148)

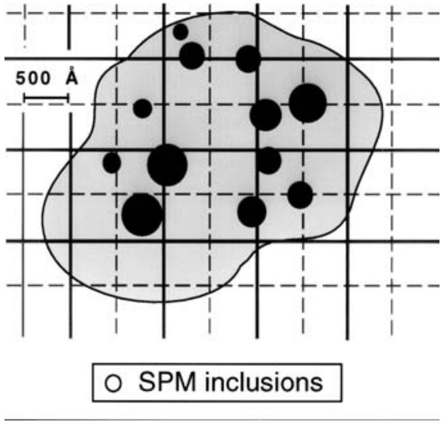
The theory of Superparamagnetic (SPM) grain alignment

Superparamagnetic (SPM) hypothesis;

Grains can align sufficiently quickly if the imaginary part of the magnetic susceptibility is greatly enhanced over that found in paramagnetic materials (Jones & Spitzer 1967)

The required enhancement can be provided quite easily by the presence of small clusters or inclusions of ferromagnetic materials such as metallic iron and iron oxides and sulphides.





The spacing of embedded “superparamagnetic” (SPM) inclusions in GEMS particles in IDPs;

∴ the spatial frequency of ~0.1μm (Goodman & Whittet et al. 1995)

→ consistent with the Mathis’s “cutoff size” of a′~0.09μm, below which no grains are aligned

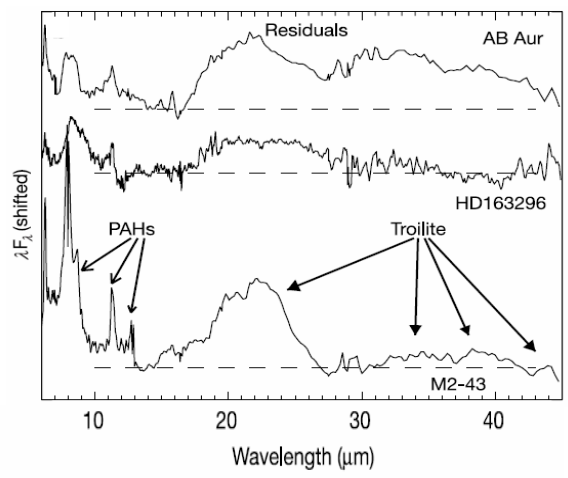
If the resemblance between the infrared spectroscopic properties of the GEMS in IDPs and those of interstellar metal sulphides obtained in the spectra of cold dense molecular clouds, the “superparamagnetic” inclusions in particles of GEMS in IDPs are expected to be preserved for interstellar grains.

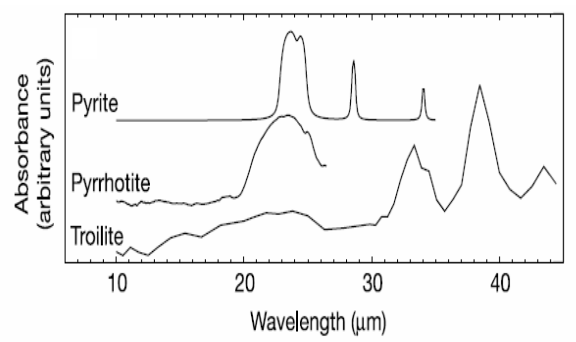
→ dust formation and grain growth in cold dense molecular clouds are suggested.

Dust formation and grain growth
in the cold dense molecular clouds are examined.

Enhanced depletion of sulphur in cold dense molecular clouds (Joseph et al. 1986)

→ cold dense molecular clouds with embedded young stellar objects in the Milky Way are favorable places to look for iron sulphide grains.





(left panel) The ISO/SWS mid-infrared spectra of young stars AB Aurigae, HD163296, and the evolved star M2-43 after subtracting the model spectra composed of amorphous silicates, metallic Fe and carbonaceous materials.

(right panel) Infrared spectra of troilite (FeS) and of pyrite (FeS_2) calculated from oprical constants, and of pyrrhotite ($Fe_{1-x}S$) from laboratory measurements.

(Keller et al. 2002, *Science*, 417, 148)

Moderate-dispersion (R>~1000) spectroscopic abilities in the mid-infrared (10-36μm) with MIRMES and in the far-infrared (35-200μm) with SAFARI are crucial to identify the mid-infrared features of iron sulphide grains at 23.5, 34, 38 and 44μm.

High-dispersion (R>10000) spectroscopic abilities in the mid-infrared (4-20μm) with MIRHES is crucial to examine the properties of molecules in cold dense molecular clouds with embedded young stellar objects in the Milky Way

Life Cycle of dust：Objective #4

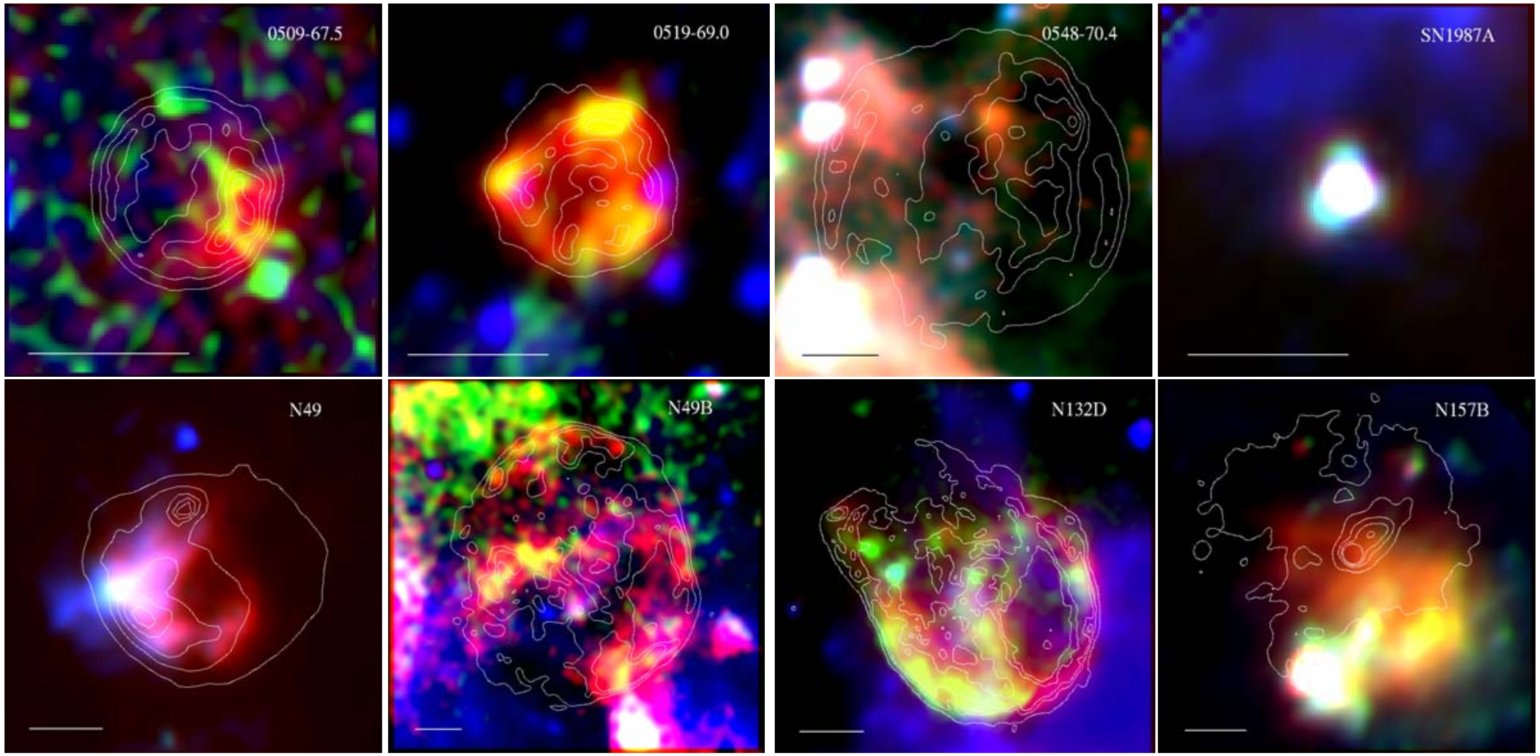
- 科学目的 Objective
  - 銀河物質進化への超新星の影響、特にダスト生成・破壊及び周囲の星間物質へのエネルギー供給過程を明らかにする
  - Elucidate the effects of supernovae on the material evolution; the formation and destruction of dust grains, and energy supply processes to the ISM
- 科学目標 Target
  - これまで赤外線で検出されている超新星残骸（系内外あわせて約30個）について、計300　時間(TBD)の中間赤外線・遠赤外線イメージ分光を行い、生成ダスト・組成・量、衝撃派の影響・ISMへの影響を調べる。Objective#5で検出されたSNRについても同様の詳細観測も行う（約100-200 時間）
  - About 30 SNRs so far detected in the infrared as well as those detected in Objective #3 will be observed with Imaging spectroscopy in the mid-to far-infrared to investigate the composition/amount of formed dust, shock effects, and effects on the ISM (In total about 400 to 500 hours).

中間赤外線低分散分光装置 MIRACLE　中分散分光装置 MIRMES
遠赤外線分光撮像装置 SAFARI （low-res. & high-res.）

Supernovae in infrared

Information on the formation and destruction of dust by SNe as well as the interaction with the ISM can most effectively obtained in infrared observations

SNRs in our Galaxy are located mostly on the Galactic plane, where the confusion on the line-of-sight is significant. SNRs in external galaxies provide a better situation with respect to the confusion, but they are smaller in size and thus requires high-spatial resolution observations, particularly in the far-infrared, which is significant in the estimate of mass of the dust grains associated with SNRs.

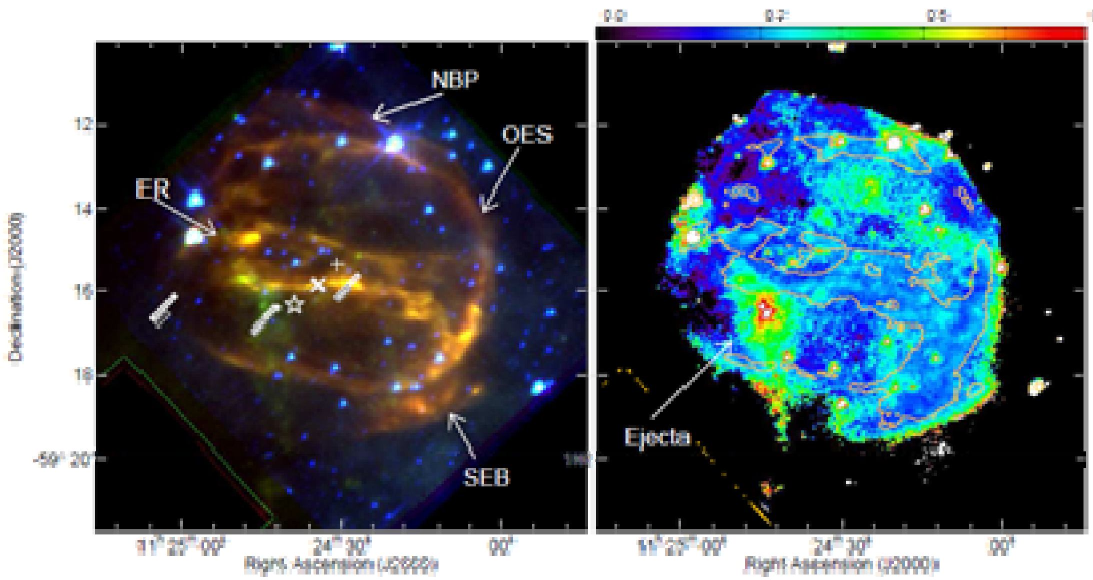


SNRs in the LMC of AKARI 7, 11, & 15μm color images (Seok et al. 2008, PASJ, 60, S453)

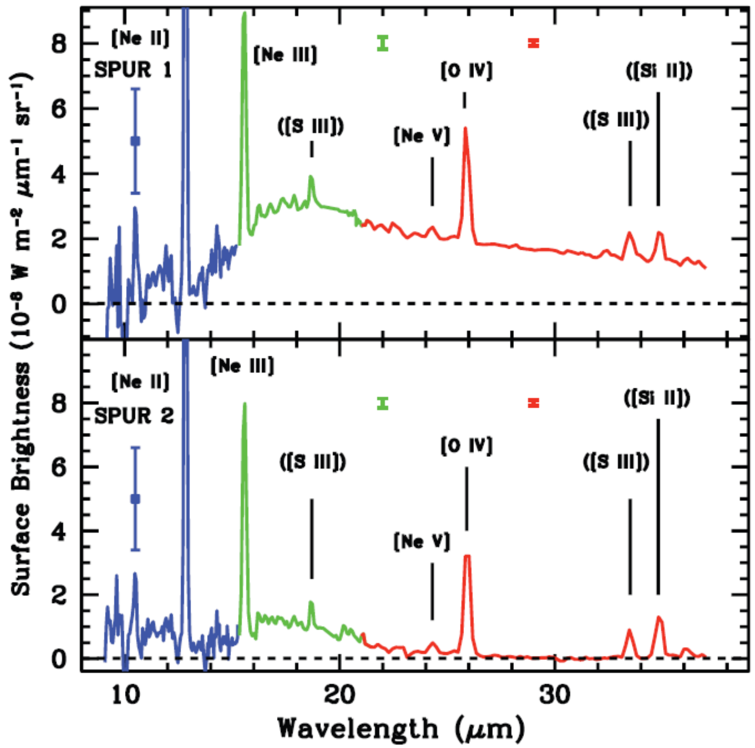
Supernovae – place for fast dust production in the Universe

Despite the significance of supernovae for dust formation, the composition and amount of dust formed is not yet fully understood. This largely owes to the poor spatial resolution of current facilities in mid-to far-infrared. It is indispensable for the study of SNRs to separate individual components (ejecta and circumstellar matter).

Because of emission lines and multi-component nature a wide range spectroscopy is important



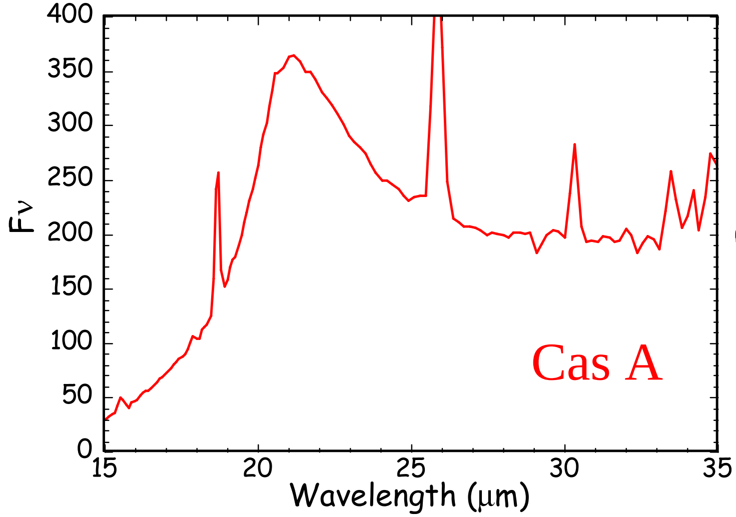
AKARI Observations of G292.0+1.8 (L) 7, 15, 24μm color (R) 15/24 ratio (Lee et al. submitted)

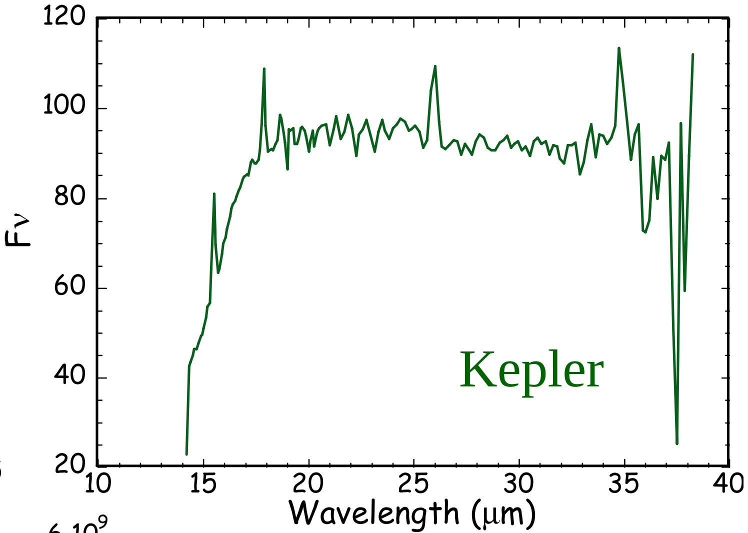


Spitzer IRS spectra of G292.0+1.8 (Ghavamian et al. ApJ in press)

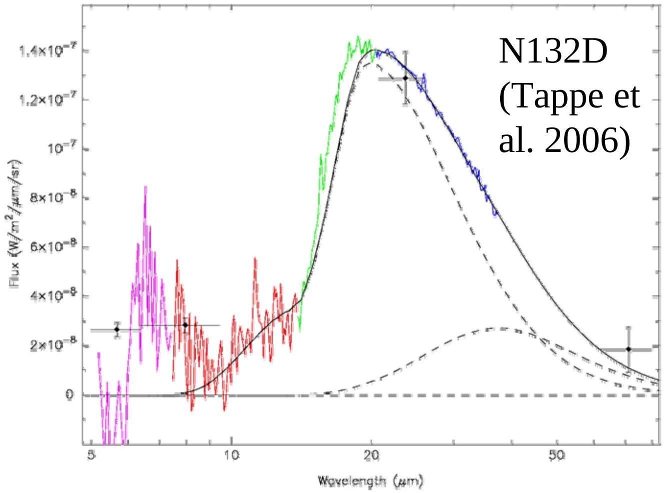
Signature of dust formed in SNe

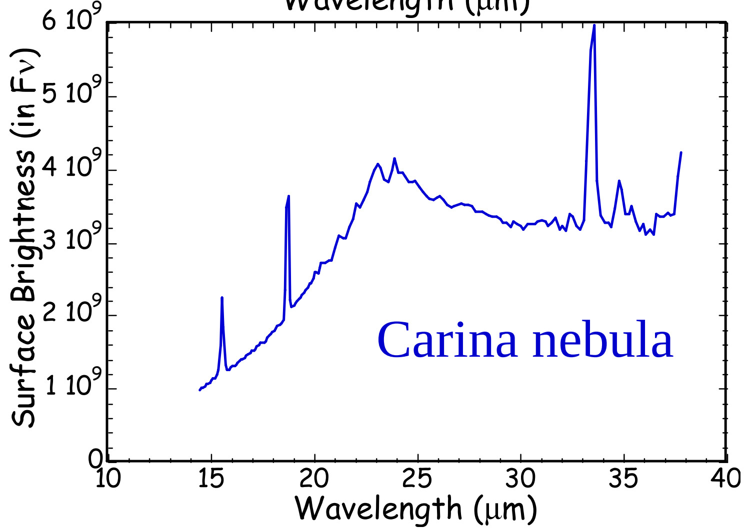
Infrared spectra have so far been obtained for only a handful of SNRs, most of which indicate the presence of a broad hump around 15 – 25μm, depending of objects.
The diversity may indicate the evolution of dust grains.
Emission lines provide information on the physical conditions and abundance





A similar hump is also seen in massive star-forming regions, indicating the relation to SNe





Several materials have been proposed, but more data are clearly needed for detailed investigations

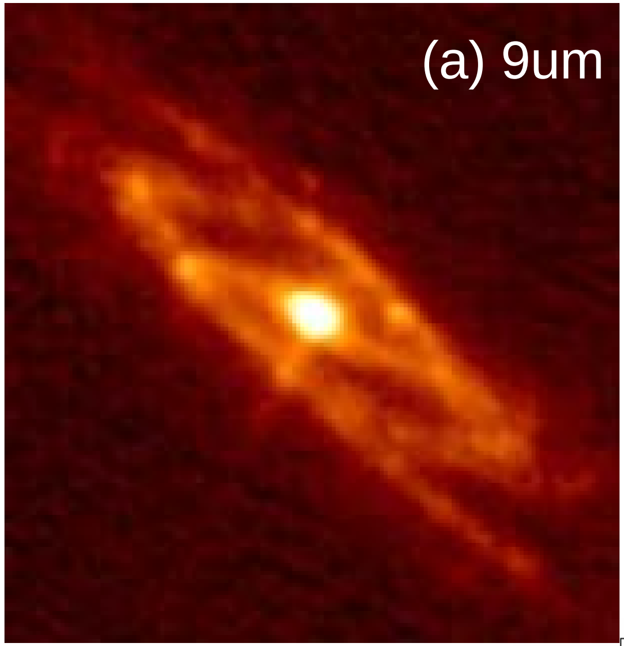
Onaka et al. (2009)

Life Cycle of dust：Objective #5

- 科学目的 Objective
  - 銀河内外の物質の流れを捉え、銀河スケールで物質の進化を理解する。
  - We understand the physical processing and chemical evolution of the ISM in galactic scales in view of material circulation for nearby galaxies.
- 科学目標 Target
  - 「あかり」サンプル近傍銀河50個に対し、計600時間の中間・遠赤外線イメージ分光により、ガス診断とダスト(バンド)観測を行う。SNR、HII領域、巨大分子雲、銀河中心、ハローなど、物質の生成・破壊場所を空間分解し、大きな循環と銀河内gradientを捉える。系内物質循環の詳細研究(#1-#4)と相補的。
  - By mid- to far-infrared imaging spectroscopy (600 hrs in total), we spectrally decompose and spatially resolve emission from the ISM in 50 nearby galaxies of our AKARI sample, to track galactic-scale material circulation from sources to sinks of the ISM in galaxies, which complements the objectives #1-#4.

中間赤外線低分散分光装置 MIRACLE　中分散分光装置　MIRMES
遠赤外線分光撮像装置 SAFARI（low-res. & high-res.）

3-D picture of ISM distributions in various gas phases



MIRACLE & SAFARI (low-res.) enable spatially-resolved spectroscopic studies of dust and gas in disks & haloes for face-on & edge-on galaxies.

Example: NGC253

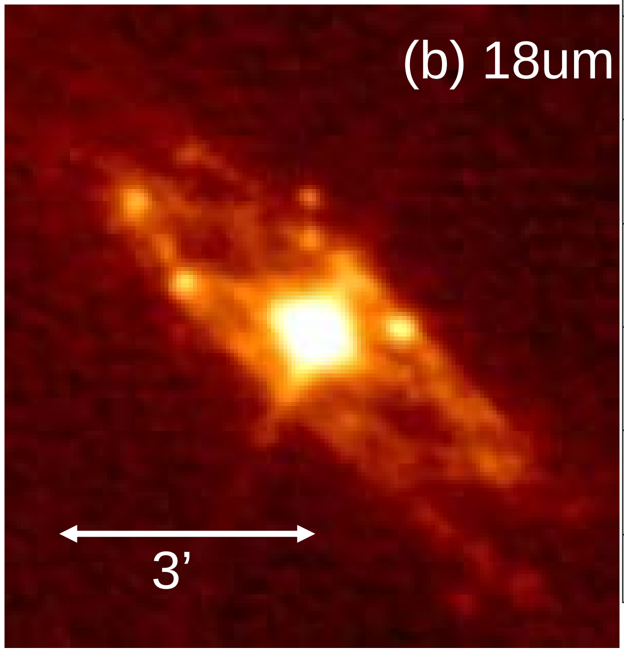
(a) AKARI 9um (PAH+old stars) (b) 18um (warm dust)

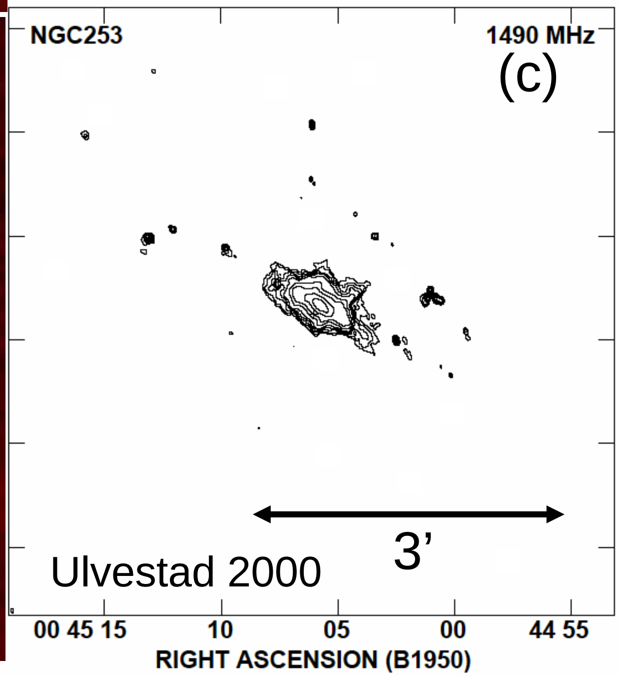
(c) VLA 20 cm continuum

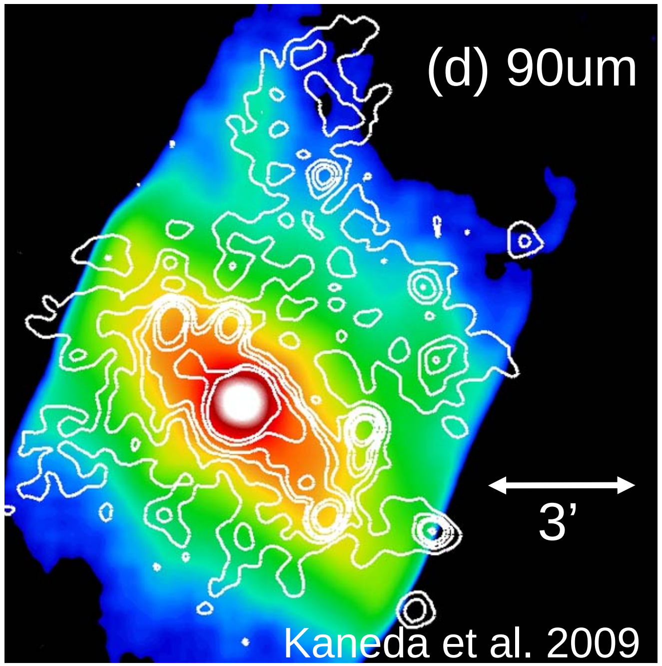
→ discrete radio sources: SNRs? HII regions?

(d) AKARI 90um in color, ROSAT X-ray in contours

→ dust outflow entrained by X-ray superwinds







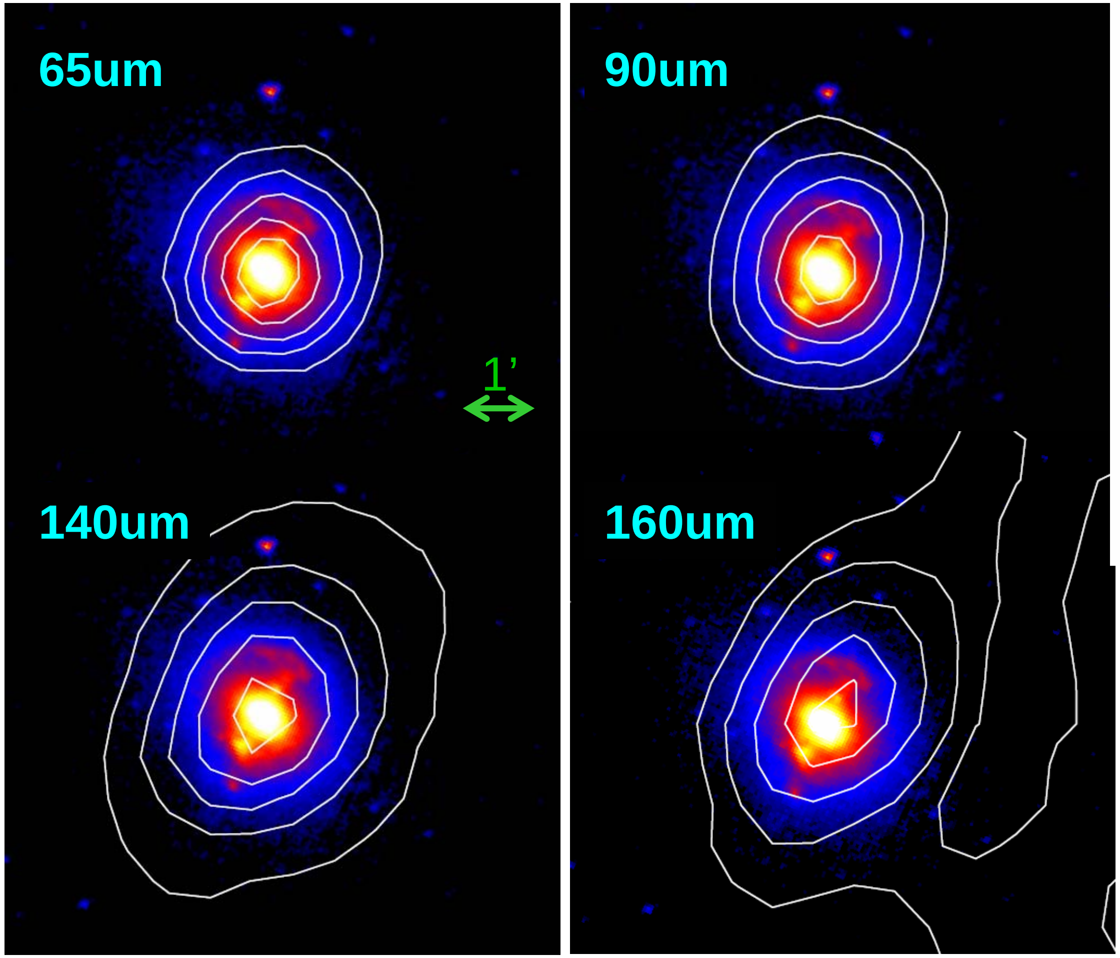
Galactic nuclei & Influence of their activities on ISM

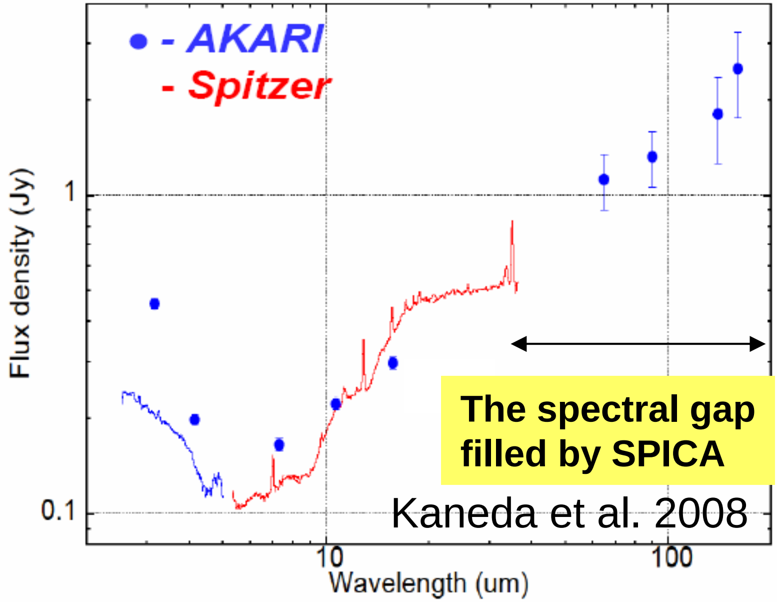
MIRMES & SAFARI (high-res.) probe central regions of galaxies by detailed gas line diagnostics, even revealing the kinematics of material circulation flow.

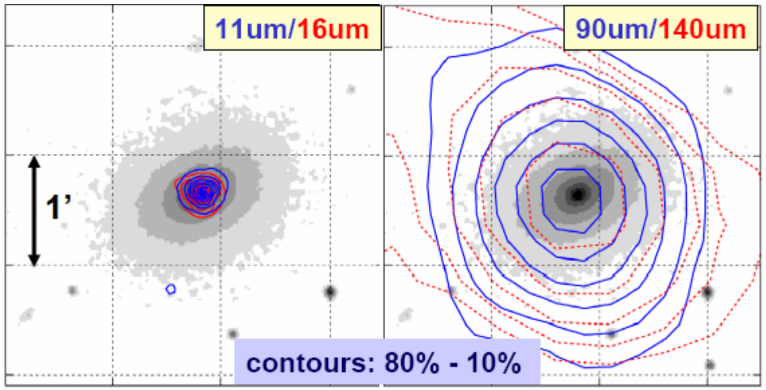
Example: (left) NGC1316: AKARI/FIS images overlaid on AKARI 11um image.

→ Energy feedback outflow from a central dust reservoir (?)

(right) NGC1052: a LINER elliptical.







Why SPICA?

- Low FIR background thanks to the cold telescope enables faint extended emission to be detected from nearby galaxies, which Herschel cannot detect.
- Small and simple PSFs in the MIR-FIR thanks to the monolithic 3.5m mirror can reliably resolve various dust and gas components in nearby galaxies.

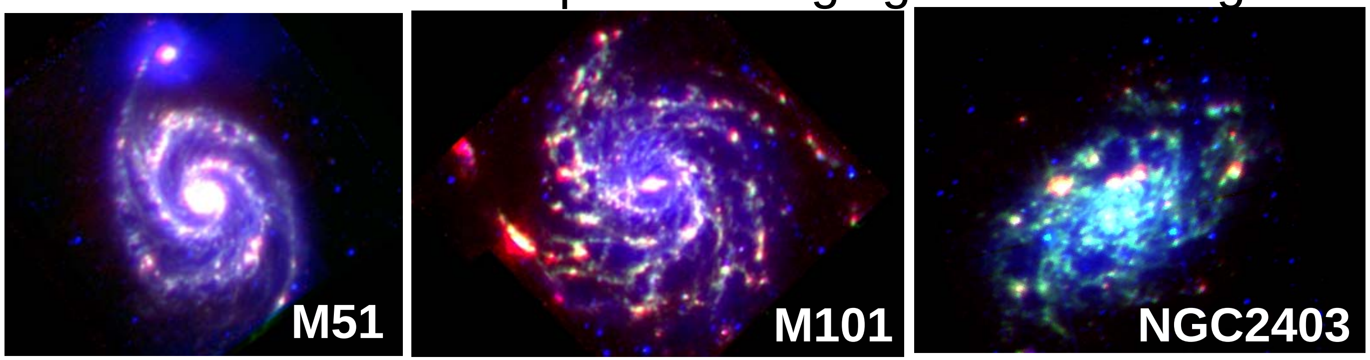
Requirements for SPICA

(1) MIR-FIR continuous spectral coverage is crucial for dust physics, maximizing outputs from the cold telescope; this would make SPICA unrivalled.

(2) MIR-FIR spectroscopic imaging capability with low - moderate spectral resolution is essential for spatially-resolved studies of nearby galaxies.

(3) For efficient mapping, we need the capability of raster mapping with variable integration time at different positions.

(4) For better calibration of extended sources, [SiII] 34.8 um line should be observed by both SAFARI and MIR instruments with matched spectral capabilities. Two different modes are compared: imaging FTS and long-slit spectral mapping.



AKARI MIR images

Life Cycle of dust : Objective #6

科学目的　Objective

　天の川銀河系の恒星分布、ダスト供給源分布、ダスト分布を明らかにし、大局的な物質循環を探る。

Census of red clump giants, dust producing objects, and dust extinction in the Galactic plane to explore the global dust circulation in the Galaxy.

科学目標　Target

　天の川銀河系の、銀経－90°から＋90°、銀緯－2°から＋2°の範囲（いわゆる銀河面）を近・中間赤外線域で撮像と分光の両面から網羅的に探査する。レッドクランプ星、長周期変光星により銀河系中心を超えて銀河系円盤部の反対側の端まで見通すことで、銀河系円盤部の恒星質量分布を得る。また、ダスト供給源である高い質量放出率を示す各種天体の分布、星間ダストの分布を得る。これらにより、銀河系内の物質循環の具体的描像を得る。

A complete survey of objects lying in the Galactic plane area of −90d ＜ l ＜ 90d and −2 ＜ b ＜ 2d in the near− and mid−infrared range will be performed in both mult−band imaging and low−resolution spectroscopic modes. The Galactic plane will be looked through by red clump giants and long period variables to the other end of the Galactic disk, which allows to examine the stellar mass distribution in the disk. The distributions of all kinds of objects will be revealed that supply abundant dust grains into the ISM. Also, dust grain distribution in the Galaxy will be examined. Life cycle of dust in the Galaxy will be depicted based on these results.

焦点面検出カメラ FPC-S
中間赤外線撮像低分散分光装置 MIRACLE　中分散分光装置MIRMES

Global dust circulation in the Galaxy

Scientific Backgrounds

Global dust grain circulation in the Galaxy not well understood
... Need knowledge on the gravitational potential in the Galaxy
The Galaxy is a spiral galaxy with a bar structure in the center
... Spiral pattern still not well defined
... Bar structure not confirmed yet in the far-side
The central structure may have substructures
... The substructure still controversial
Many high mass-loss stars are found near the center of the Galaxy
... They dominate mass and dust return rates in the local space

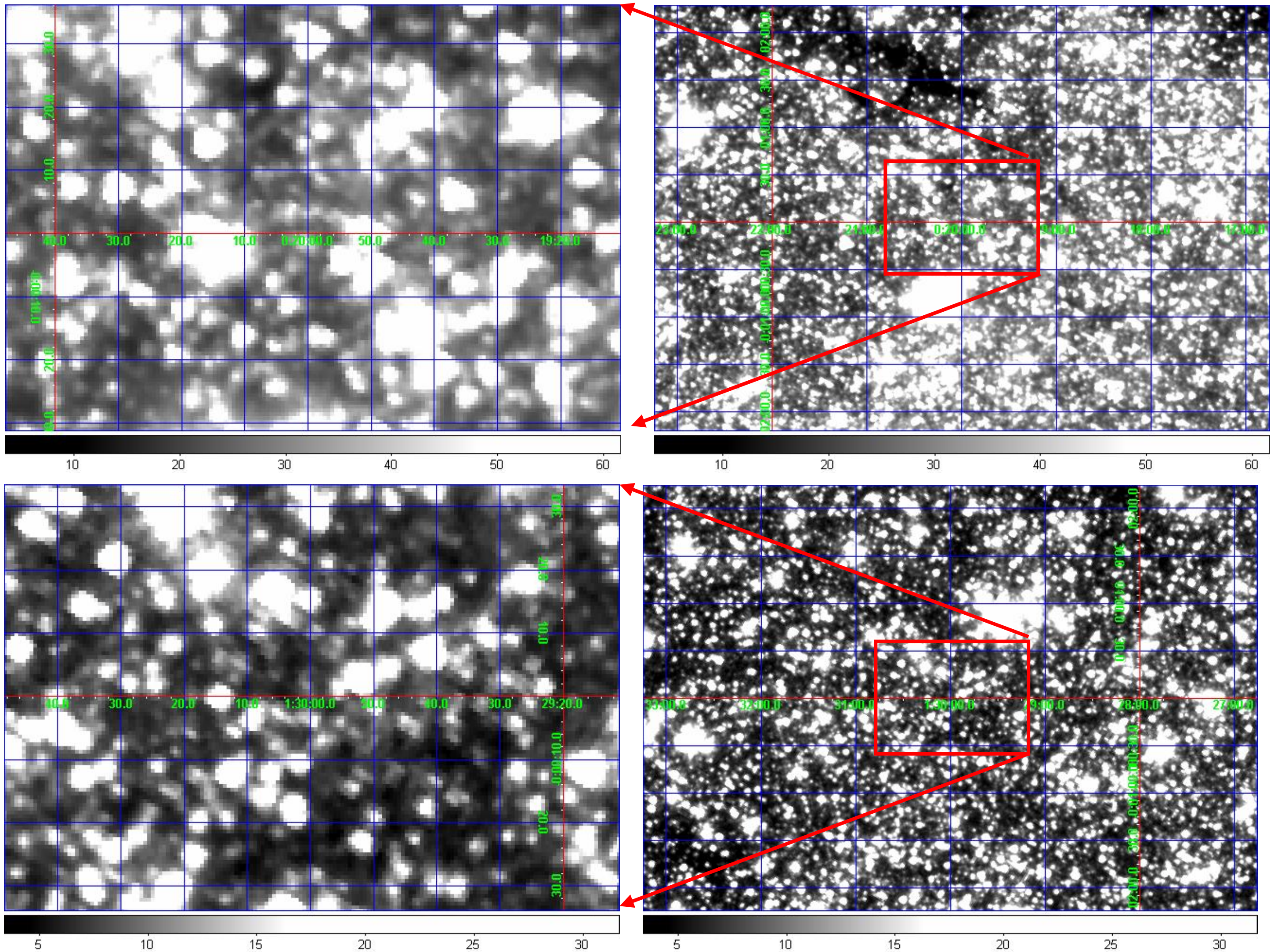
<u>Issues to be solved</u>

-- Stellar mass distribution in the Galaxy
- Shapes of the bulge, bar, arms, and disk.

-- Distributions of high mass-loss objects in the Galaxy
- Dominant contributor to the interstellar dust recycling

-- Dust distribution in the Galaxy
- Ejected dust grains accumulated over their life cycle

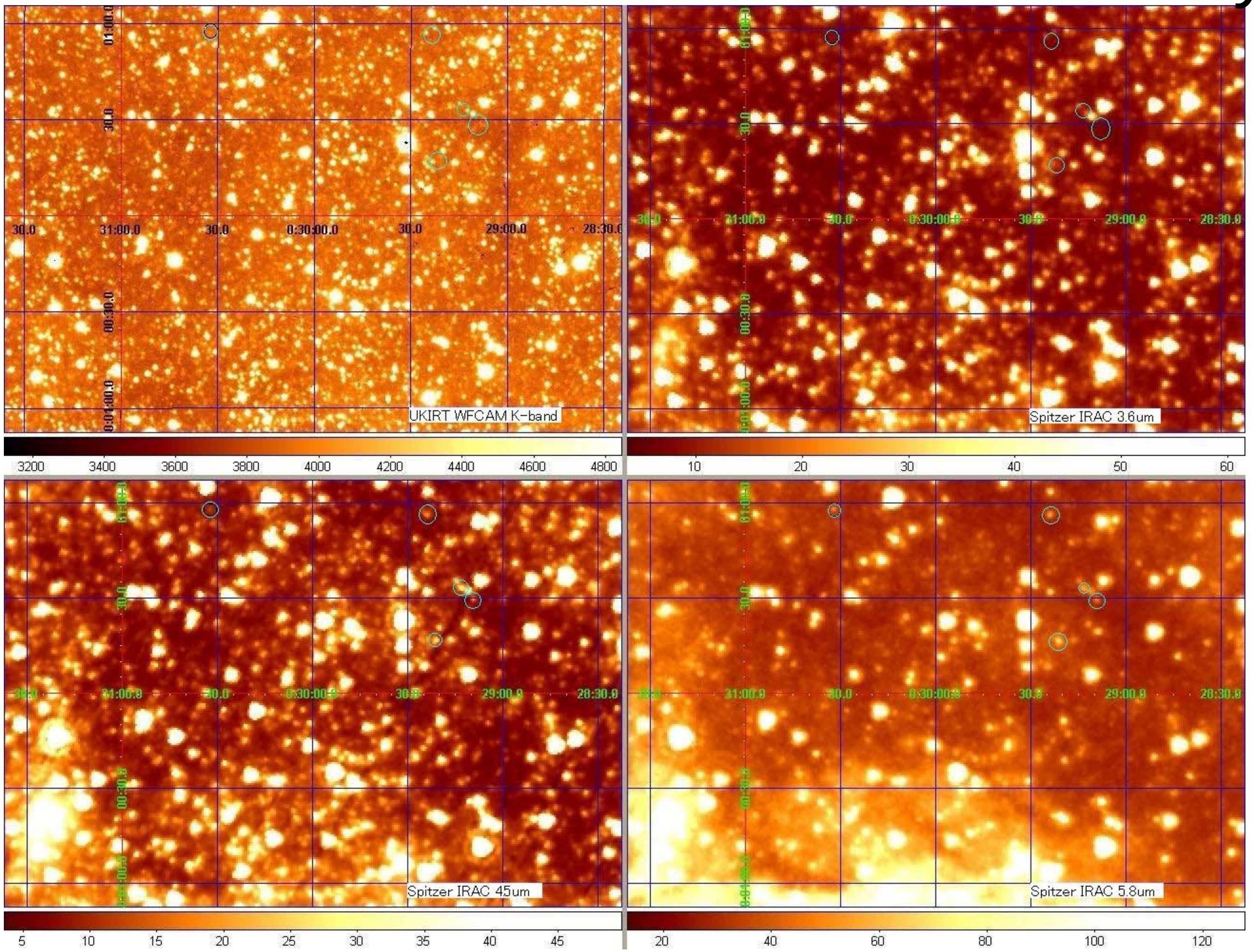
Global dust circulation in the Galaxy



Spitzer GLIMPSE (0.6”/pixel,10” grid) Galactic Plane near G. C. @3.6um

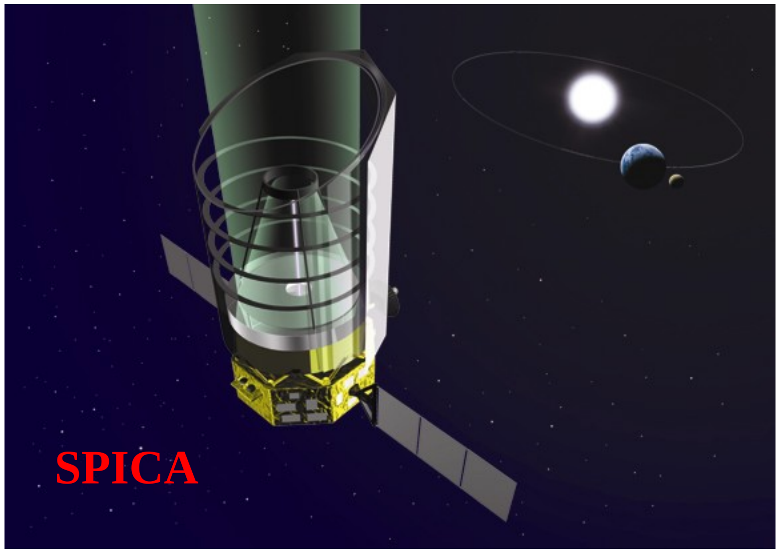
High resolution (PSF~0.7”) and high sensitivity imaging with FPC-S and MIRACLE is essential for further resolving and measuring faint crowded stars in the Galactic plane.

Global dust circulation in the Galaxy



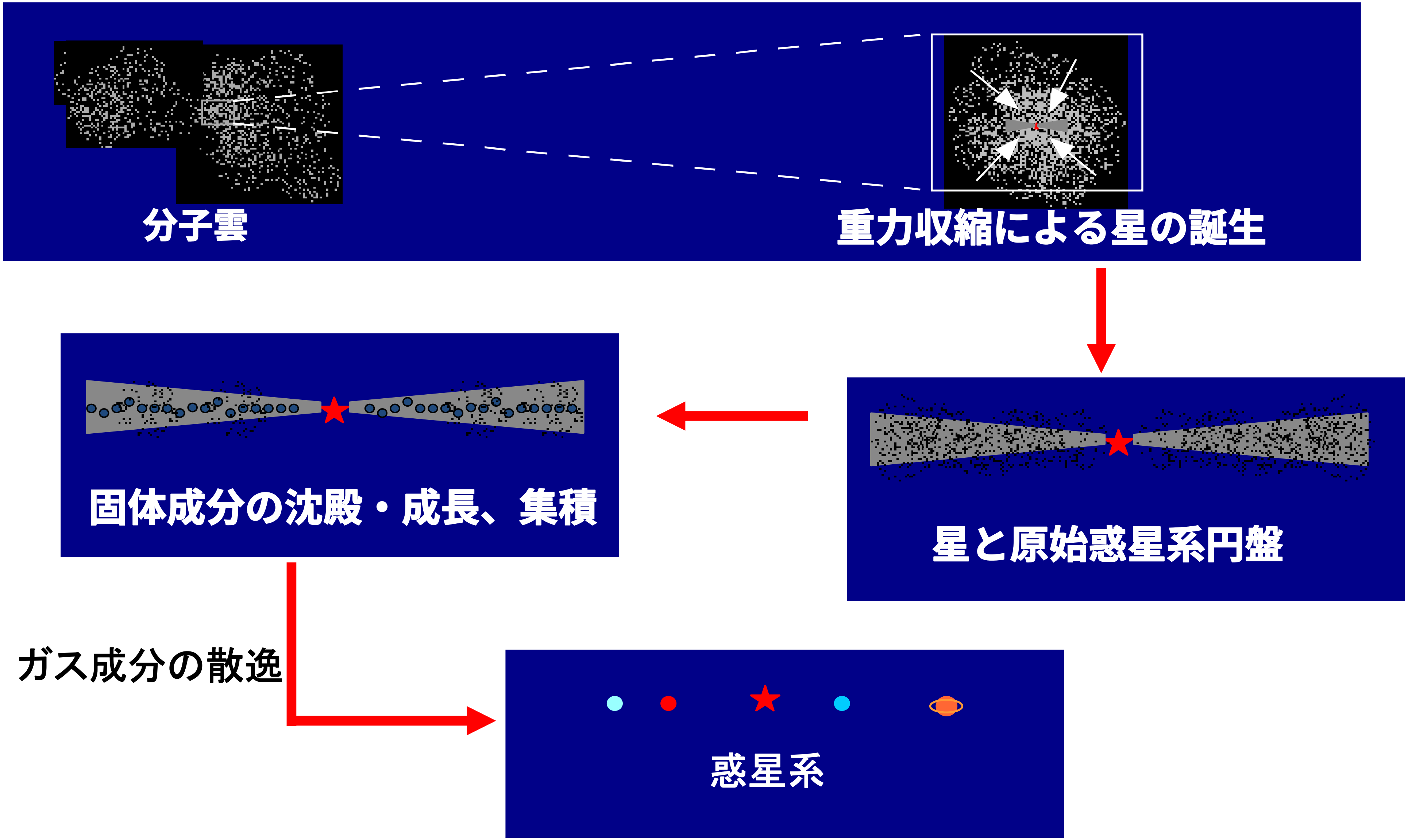
L and M band imaging with FPC-S and MIRACLE is indispensable for detecting stars with thick circumstellar dust shells as indicated by blue circles.
Low resolution spectroscopic survey with MIRACLE is unique and powerful to characterize the sources seen in the imaging survey.

Major Objective [3]
惑星系形成過程の総合理解
-Thorough Understanding of Planetary System Formation-

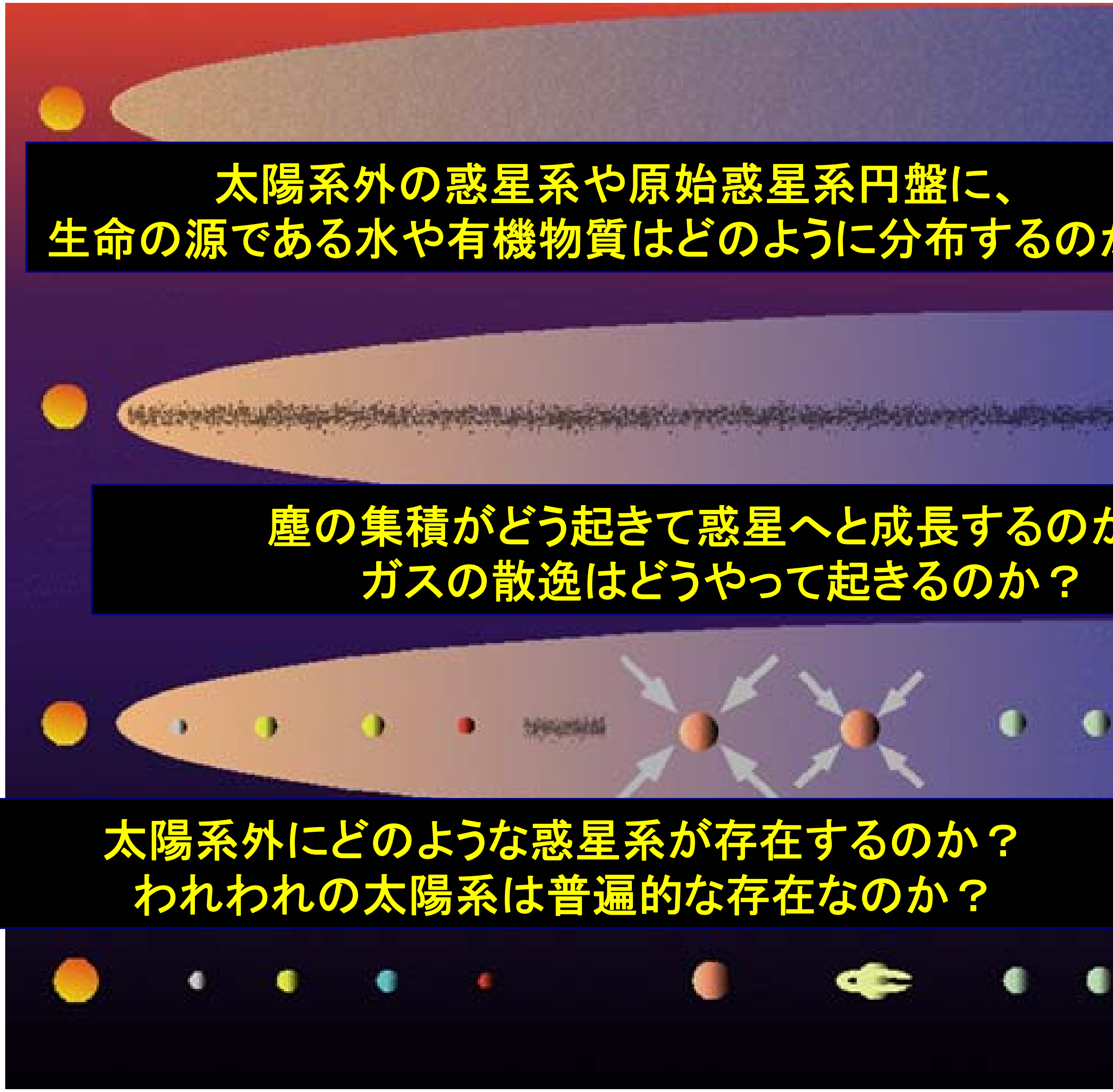


惑星系形成過程の総合理解

-Thorough Understanding of Planetary System Formation-



惑星系形成のパラダイム



原始惑星系円盤
（ガスと塵の集まり）

太陽系外の惑星系や原始惑星系円盤に、
生命の源である水や有機物質はどのように分布するのか？

塵が赤道面に集積(？)

塵の集積がどう起きて惑星へと成長するのか？
ガスの散逸はどうやって起きるのか？

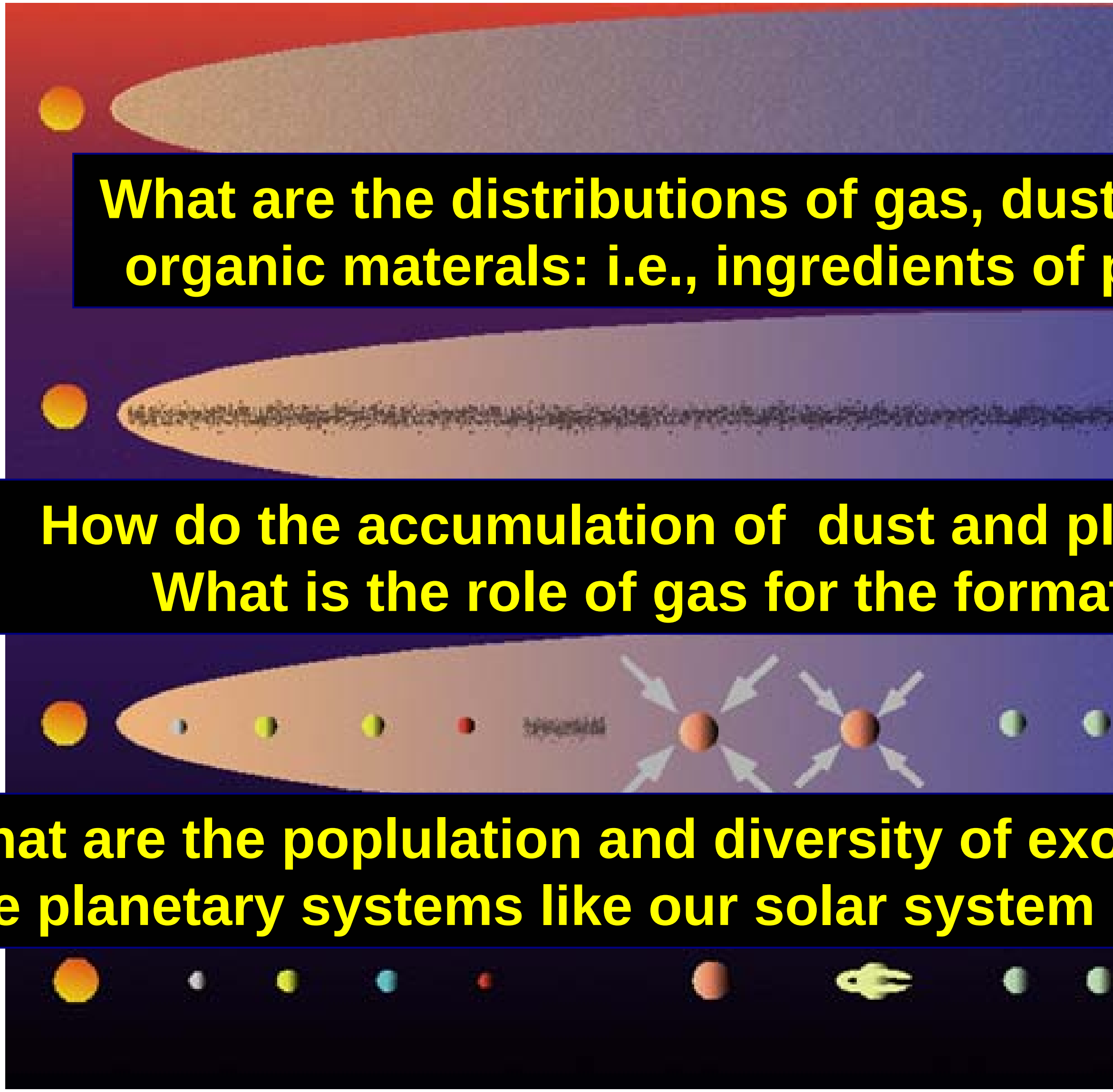
地球型惑星の誕生(？)

太陽系外にどのような惑星系が存在するのか？
われわれの太陽系は普遍的な存在なのか？

ガスをまとって
木星型巨大惑星に(？)

惑星系

Open Questions



Protoplanetary disk
with gas and dust

What are the distributions of gas, dust, woter ice and organic materals: i.e., ingredients of planets & life?

Dust settling (?)

How do the accumulation of dust and planetesimals occur?
What is the role of gas for the formation of planets?

Fomation of cores(?)
Gaseous accretion (?)

What are the poplulation and diversity of exoplanetary systems?
Are planetary systems like our solar system common or unique?

Planetary systems (?)

Planetary Systems：Objective #1

- 科学目的 Objective
  - 惑星系の多様性解明のため、太陽系外惑星の直接検出と惑星大気組成の観測を、最も観測的に有利な波長である赤外線領域において挑戦する。
    - To understand the diversity of the planetary systems, we will attempt to directly detect exoplanets and to measure their atmospheric composition in the infrared wavelengths.
- 科学目標 Target
  - 主星：惑星のコントラスト比10^{-6}以上の観測を実現することにより、系外木星型惑星を直接に検出すると同時に、分光観測によりその大気の組成を明らかにする。これを我々の太陽系の惑星系と比較することにより、惑星系の多様性を解明する。
    - With the planet/star contrast ratio of 10^{-6} or better, we will directly detect gas exoplanets, and perform their spectroscopic observations to clarify the composition of the atmosphere. Comparison with the results on our Solar System planets enables us to reveal the diversity of the planetary systems.
  - トランジット法を利用した分光観測により、巨大地球型惑星の大気検出を試みる。木星型惑星については、多数の赤外分子バンドの観測を通し大気組成を詳細に調べる。
    - With the spectroscopic observations utilizing the transit method, we will try to detect the atmosphere of giant earth-like planets. We will also apply the same approach to gas giant planets for detailed studies of their atmosphere.

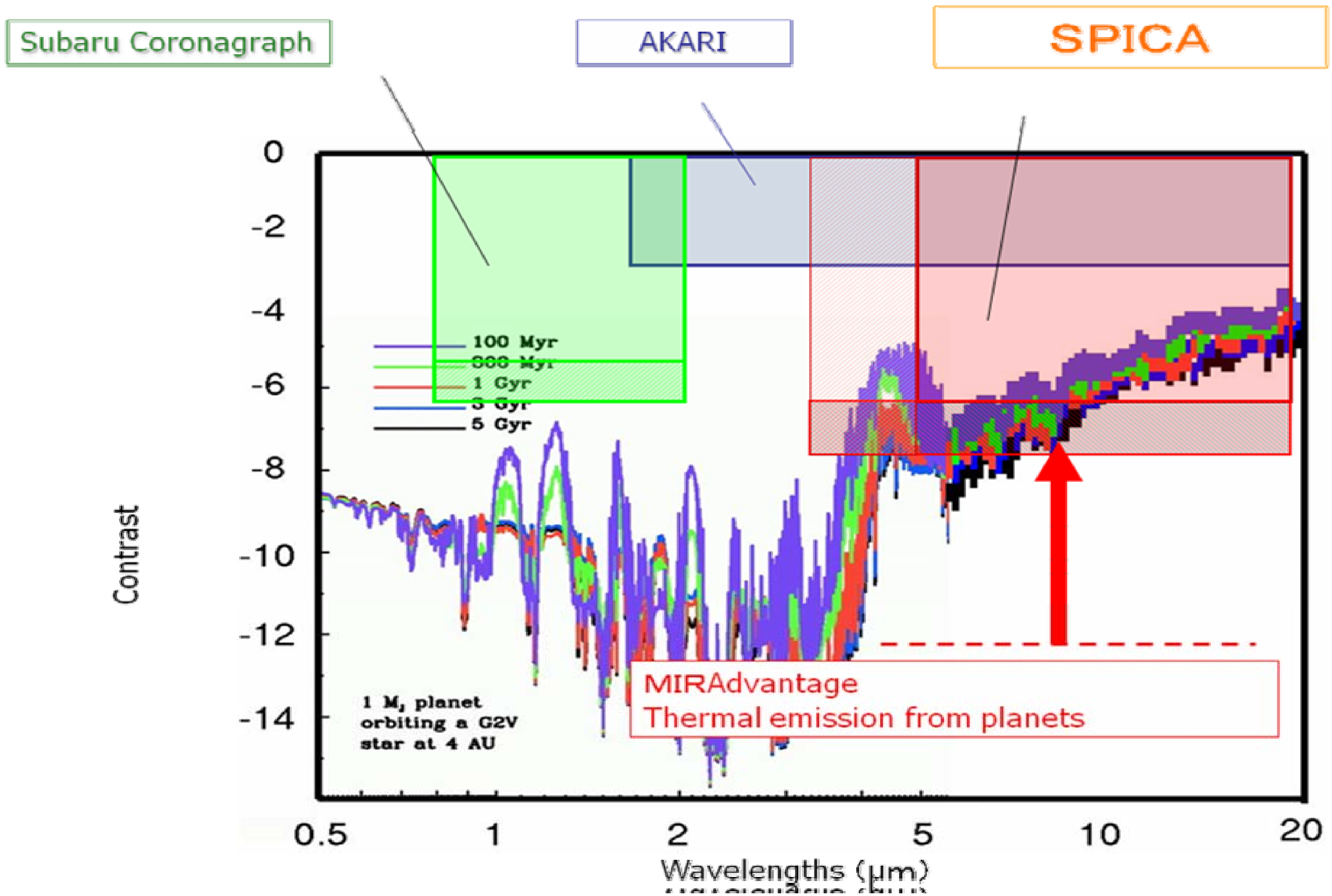
中間赤外コロナグラフ　SCI

中間赤外線中分散分光装置　MIRMES

中間赤外線高分散分光装置　MIRHES

太陽系外惑星を赤外線の目ではっきりと見つける

- 太陽系外惑星の直接検出とその大気組成観測
  - 中間赤外コロナグラフ観測装置（撮像＋分光）



Planetary Systems：Objective #2

- 科学目的 Objective
  - 原始惑星系円盤のガスの散逸過程および散逸時間スケールを観測し、木星型惑星の形成メカニズム、および地球型惑星の生成条件を明らかにする。
    - We reveal the formation mechanism of gas giant planets and initial condition of terrestrial planet formation, by observing the process and timescale of dispersing gas in protoplanetary disks
- 科学目標 Target
  - 原始惑星系円盤中のガス、特に主成分である水素分子ガスを赤外線高感度観測により検出し、残存ガスの量を求め、主星の質量や年齢との相関を解明する。
    - With sensitive infrared spectroscopic observations, we will measure the gas in proto-planetary disks, especially molecular hydrogens, and resolve the relation of gas mass with the age of primary stars.

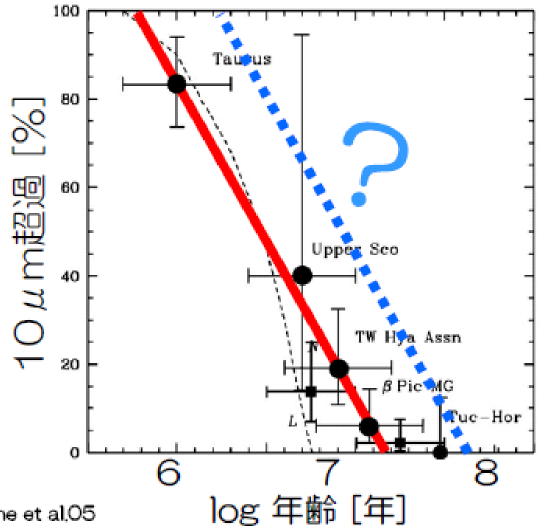
中間赤外線中分散分光装置　MIRMES

中間赤外線高分散分光装置　MIRHES

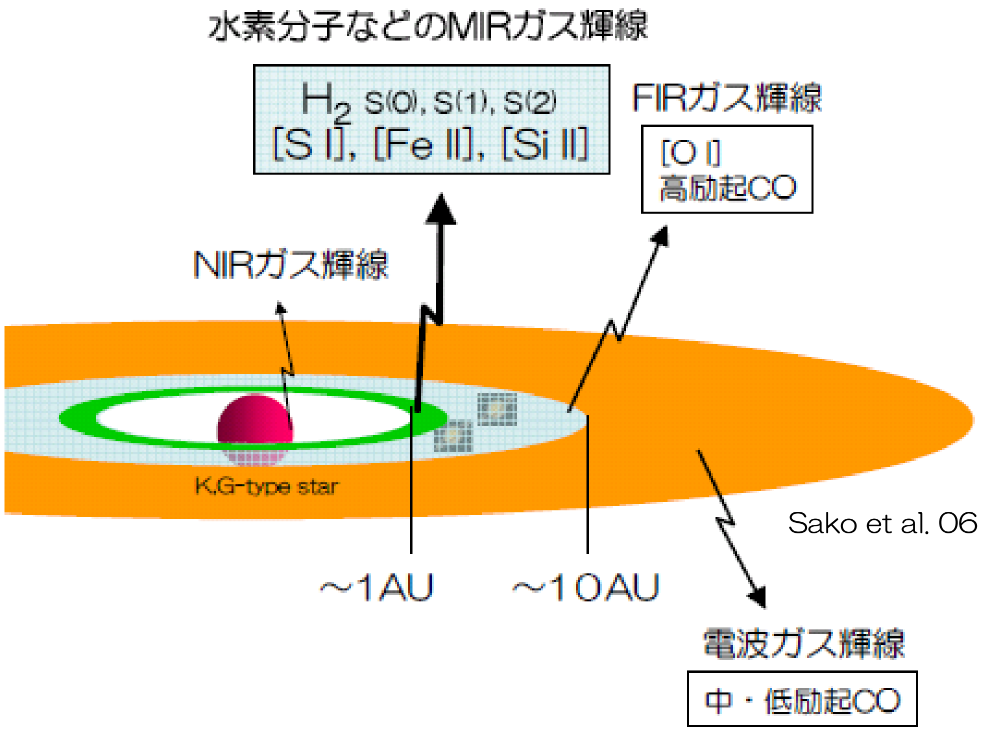
遠赤外線分光撮像装置　SAFARI

水素分子輝線で見る円盤ガス成分の進化

- ガス成分を直接トレースする水素分子輝線で、ガス円盤の温度・質量・サイズを求める
  - 中間赤外線分光装置による観測
  - 地球質量の千分の一までの水素分子質量をトレース
  - 他の分子ガスは遠赤外線分光でも観測



Silverstone et al.05



Sako et al. 06

- 円盤ガス成分の進化を解明し、惑星誕生のシナリオを完成させる

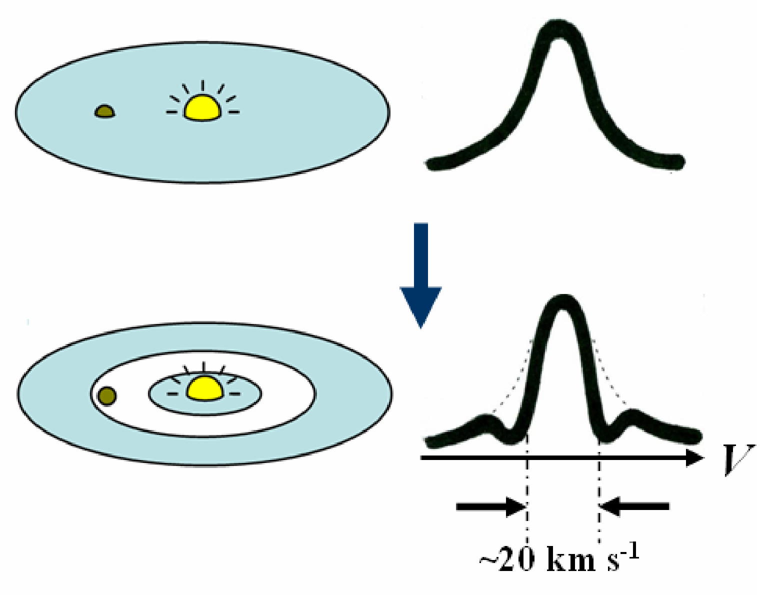
Planetary Systems：Objective #3

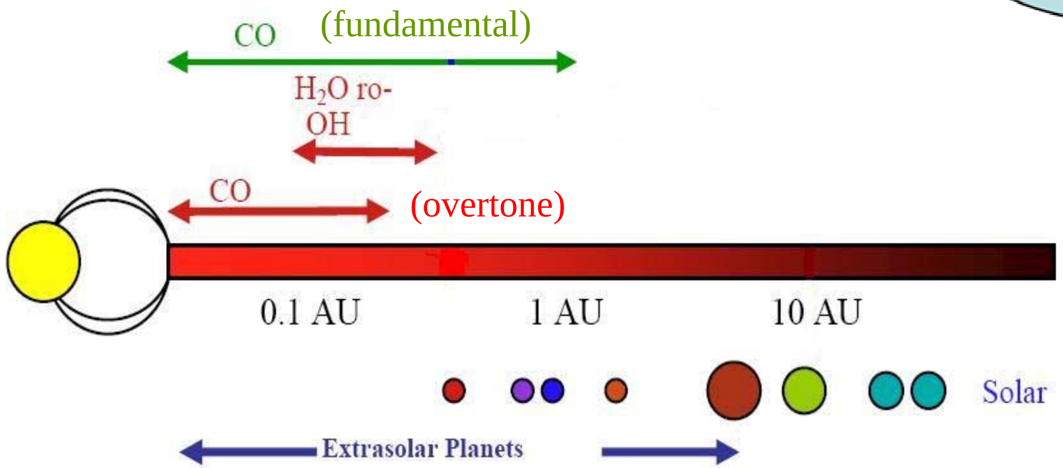
- 科学目的 Objective
  - われわれの太陽系と同様の空間スケールで、惑星系形成により原始惑星系円盤がどのように進化していくかを解明する。
    - We will reveal the evolution of planet forming regions in protoplanetary disks at a spatial scale comparable to our Solar system.
- 科学目標 Target
  - 原始惑星系円盤の高分散赤外線分光観測により、ガスのさまざまな速度成分の輝線強度比を求め、それに基づき円盤の空間構造、物理状態、化学組成の分布を明らかにする。
    - We will elucidate the geometric, physical and chemical structure of proto-planetary disks by measuring the motion of gas with high-dispersion infrared spectroscopy.

中間赤外線高分散分光装置　MIRHES

ガスの運動から円盤構造をとらえる
Revealing the Disk Structure through the Gas Motion

- ガスの運動から、円盤の幾何構造や化学組成の分布を探る
  - 中間赤外高分散分光装置





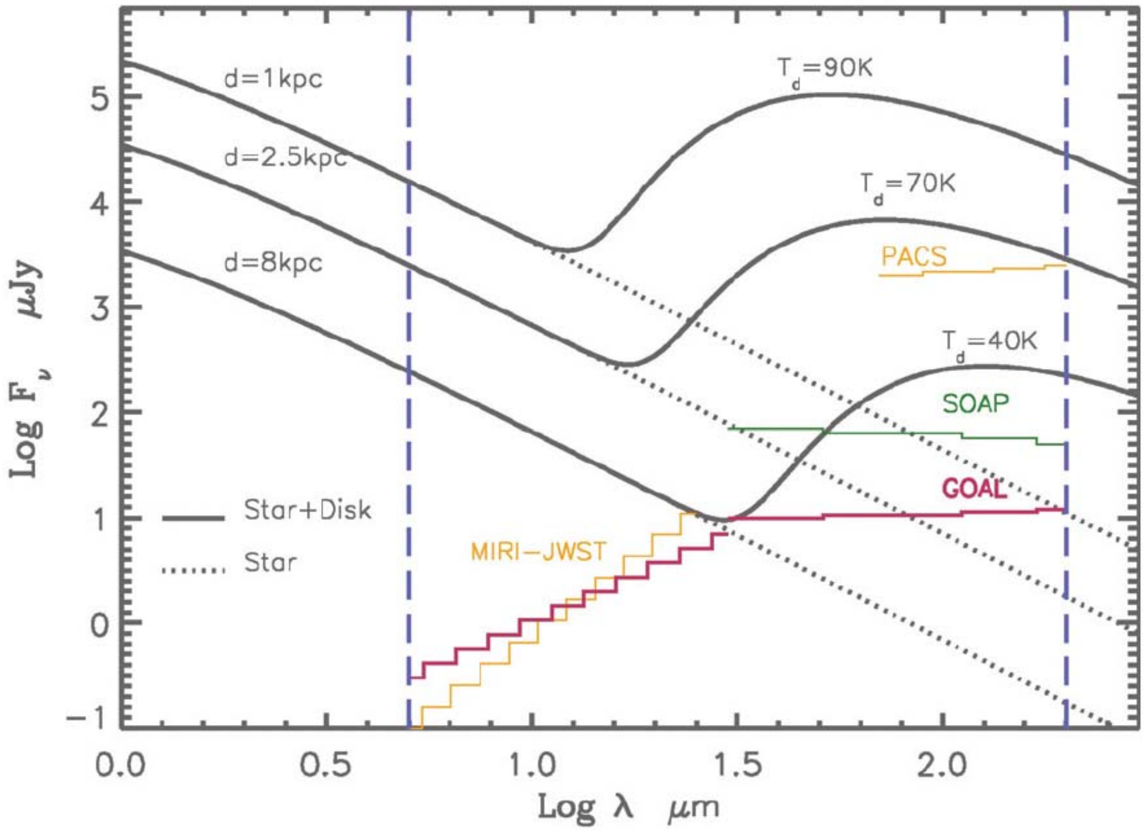
Planetary Systems：Objective #4

- 科学目的 Objective
  - 多数の主系列星周りの塵円盤の観測により、惑星系の普遍性および多様性を理解する。
    - We reveal the similarity or diversity of extrasolar systems by observing a number of debris disks, which are much more easily observable than exoplanets.
- 科学目標 Target
  - 「あかり」よりも3倍以上良い空間分解能と10倍以上すぐれた感度により、太陽系と同程度の塵しかない円盤まで検出し、惑星系と塵円盤と相互関係を解明する。
    - With the help of 3 times or more higher spatial resolution and 10 times or more higher sensitivity than AKARI, we will detect a number of disks whose amount of dust of even comparable to our solar system, leading us to understand relationship with planetary systems observed using the other methods.

中間赤外線撮像装置　MIRACLE　中間赤外コロナグラフ　SCI
遠赤外線分光撮像装置　SAFARI

主系列星の塵円盤の調査
Dust Disks around the Main-Sequence Stars

・SPICAの高感度赤外線観測で、あかりやスピッツァーが検出したものより、約10倍の距離にある恒星のまわりの塵円盤を多数検出できる。



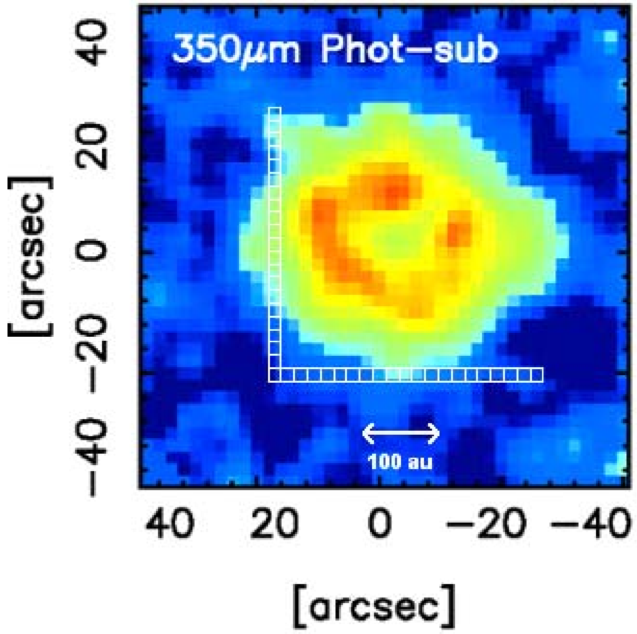
Planetary Systems：Objective #5

- 科学目的 Objective
  - 惑星系形成過程における氷の役割と、生命の起源につながる固体物質の供給仮定を解明する。
    - We will reveal the role of ice for planet formation, and how the elements for originating and sustaining life could be supplied to terrestrial protoplanets.
- 科学目標 Target
  - コロナグラフを用いて原始惑星系円盤および主系列星の塵円盤の高感度観測を行い、その進化的関係を明らかにする。
    - We will apply high-contrast IR corpnagraphy to protoplanetary disks and debris disks, observe their structures, and understand their relationship for disk evolution.
  - 主系列星の塵円盤を、「あかり」よりも3倍以上良い空間分解能で赤外線分光観測し、固体物質、特に氷および微小惑星帯の分布や物理状態を明らかにする。
    - Through infrared spectroscopic observations with 3 times or higher spatial resolution than AKARI, We will reveal distribution and physical state of solid materials, particularly ice, in proto-planetary disks and dust disks in the main-sequence stars.

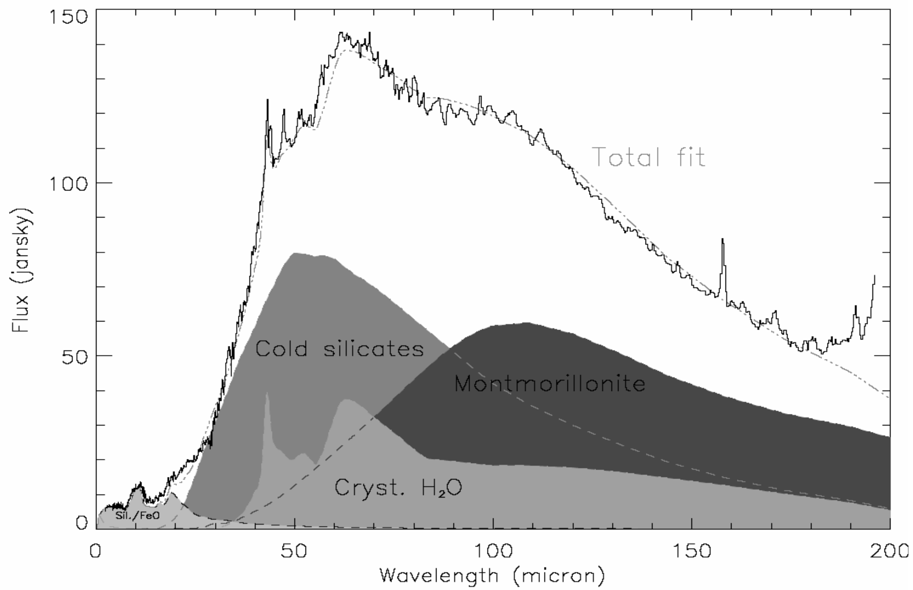
中間赤外コロナグラフ　SCI　中間赤外線撮像装置　MIRACLE
遠赤外線分光撮像装置　SAFARI

塵円盤の固体物質

- 氷（惑星材料＆生命をもたらす水）の分布と物理状態
  - 中間・遠赤外線撮像分光装置による観測



The CSO SHARCII 350um image of Vega (Marsh et al.) with SAFARI pixel scale at 43-62um overlaid. Spatial resolution equivalent to ~23 AU will be enough for observing the snow-line predicted at 42 AU.



ISO spectrum of dust and ice features associated with a young cirurumcstellar disk in HD 141517 (Malfeit et al. 1999)

Planetary Systems：Objective #6

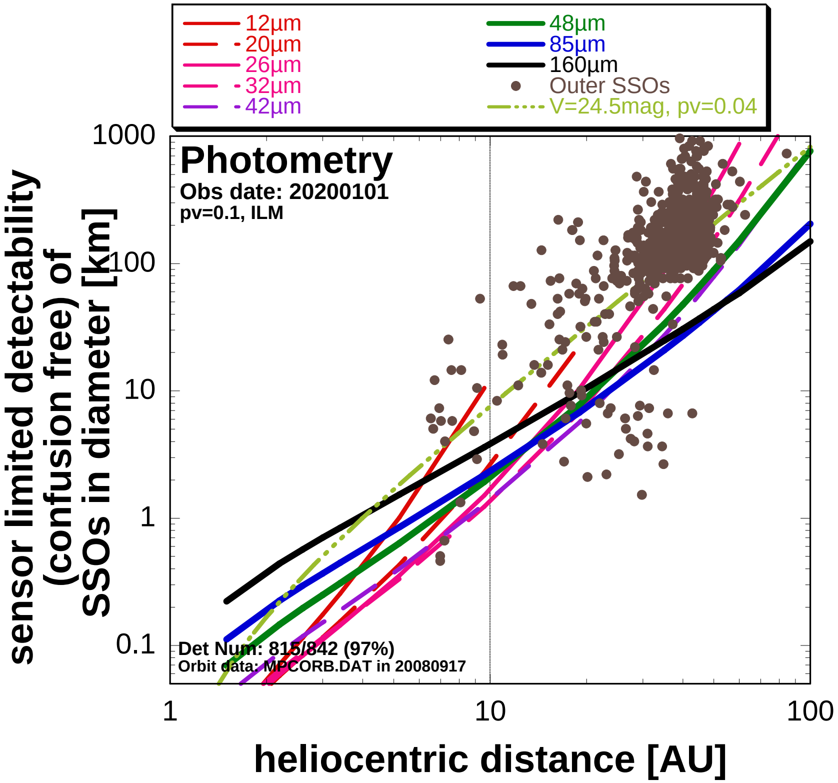
- 科学目的 Objective
  - 我々の太陽系の姿を明確にし、探査機による太陽系天体の観測結果と天文学的手法による惑星系観測結果を結ぶ為、太陽系内の始原天体の物理的情報を太陽系外縁部まで調査する。
  - In order to reveal the whole picture of the solar system, we will survey physical information for primordial objects in the solar system.
- 科学目標 Target
  - 「あかり」よりも10倍以上すぐれた感度により、太陽系内始原天体のアルベド・サイズ・熱慣性・組成を太陽系外縁部まで調査する。
  - With the help of 10 times or more higher sensitivity than AKARI, we will make an unprecedented survey of albedo, size, thermal inertia, and surface composition for primitive objects in the solar system.

遠赤外線分光撮像装置　SAFARI
中間赤外線撮像・低分散分光装置　MIRACLE
中間赤外線高分散分光装置　MIRHES

太陽系小天体の探査
Survey of Our Solar System

- Establishment of comprehensive catalogue of albedo, size, and thermal inertia for primitive objects in the solar system (SSOs);
  - near-Earth objects, main-belt asteroids, Jovian Trojans, Centaurs, Trans-Neptunian objects, comets (photometry with MIRACLE & SAFARI)
- Systematic search of surface materaial for SSOs (spectroscopy with MIRHES & SAFARI)
  - Determination of size distribution of NEAs, MBAs (>0.1km in diameter), Jovian Trojans (>0.3km), and TNOs (>30km)
  - Study of correlation among the physical and dynamical properties for SSOs

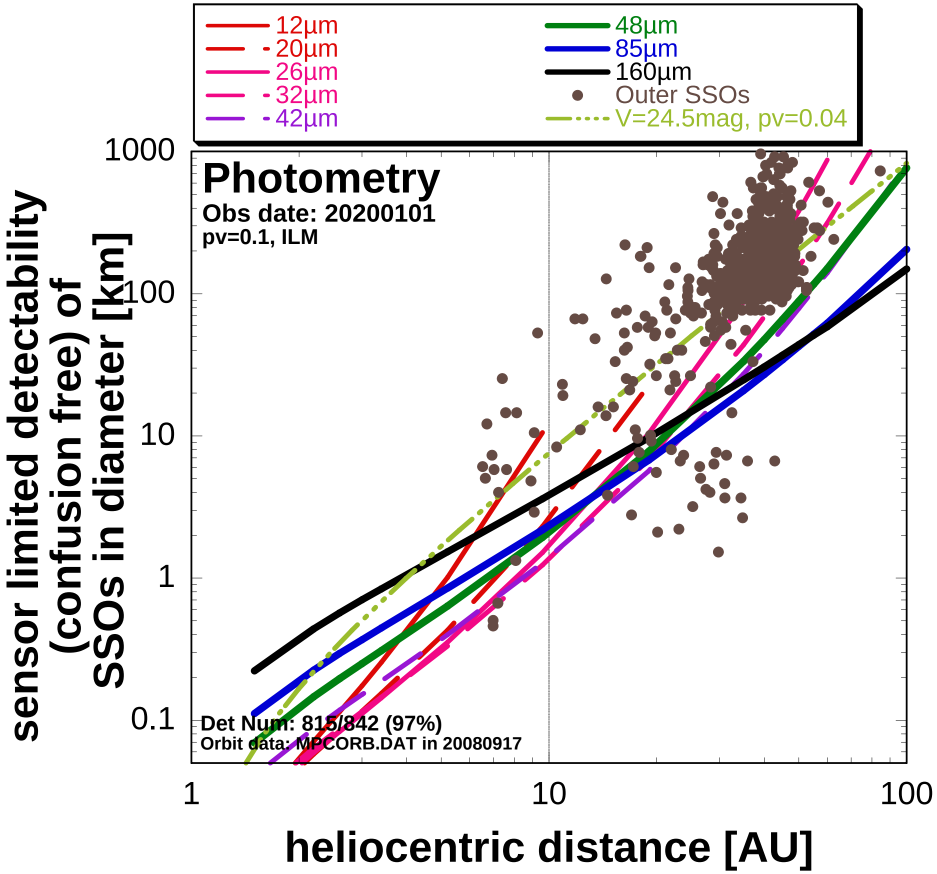
SAFARI/SPICA will detect most discovered outer SSOs (and the SSOs which will be discovered in the future) by photometric-mode and half of discovered outer SSOs by spectroscopy.



太陽系始原天体の探査
Survey of Our Solar System

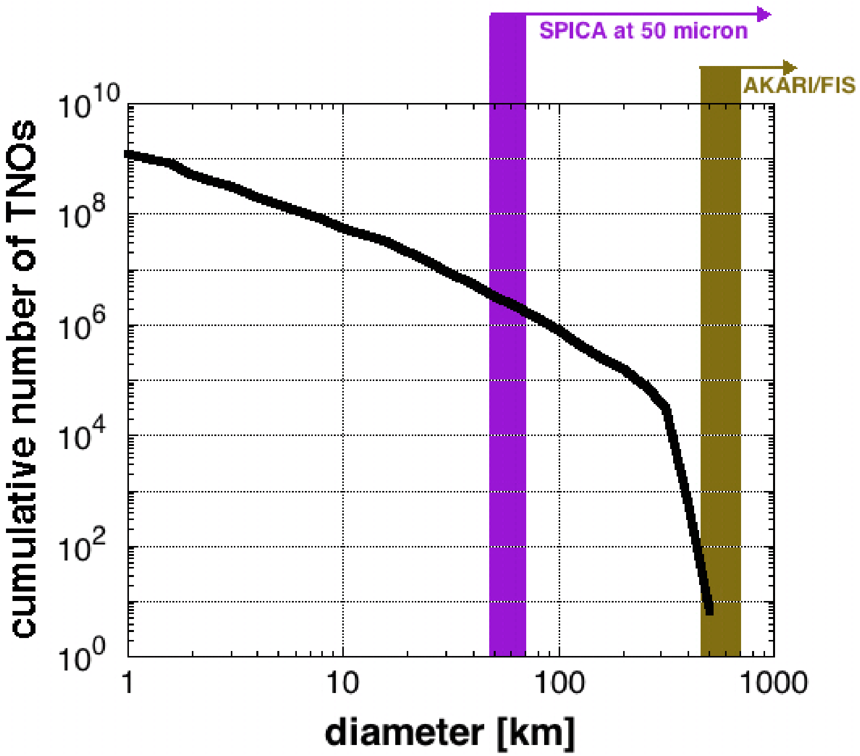
- 始原天体の熱輻射観測によるアルベド・サイズ・熱慣性の決定
  - 中間・遠赤外線による測光観測
  - 衛星・近地球型小惑星・メインベルト小惑星・木星トロヤ群・太陽系外縁部天体・短周期彗星・長周期彗星のアルベド・サイズ・熱慣性
  - 各始原天体をグループ分けし、太陽系形成・進化に関連する物理的情報を統計的に調べる

- 分光観測による組成探査
  - 中間・遠赤外線による分光観測
  - 彗星の揮発性成分探査



SPICAは、現在までに発見されている殆ど全ての外縁天体の測光観測と、約半分の天体の分光観測が可能。また将来HSC/SubaruPan-STARRS・LSSTで発見されうる太陽系内小天体についても殆どの測光観測が可能である

太陽系外縁部の探査
Survey of Outer Solar System



太陽系外縁天体のサイズ（直径）に対する累積ヒストグラム（ Davis, Farinella 1997を基に計算）。

太陽系外縁天体（TNO）のSED例。TNOのサイズとアルベドを決めるには、遠赤外線観測が重要。SPICAであれば、60AU でも観測可能な天体がある