June 1-2, 2009, SPICA Science Workshop

Studying Exoplanets and Planetary Systems Using SPICA

— Discussion to Date —

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+
…

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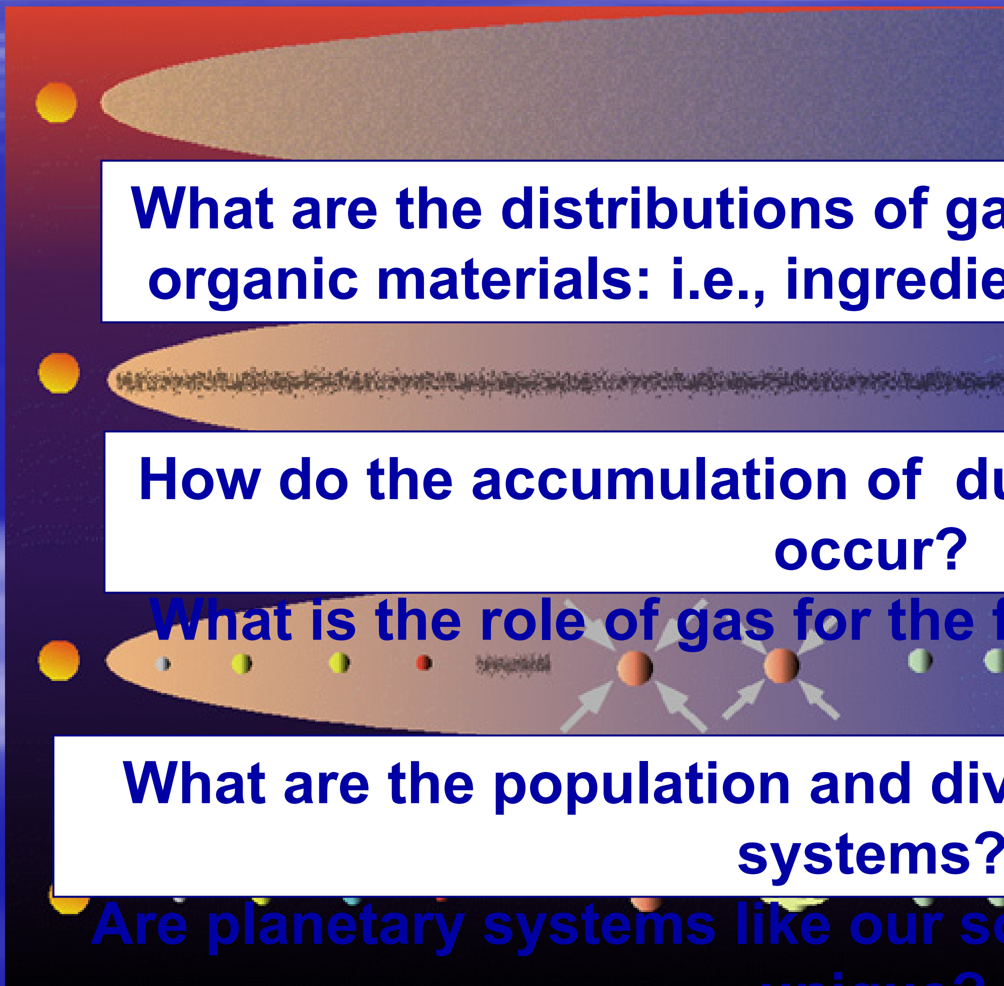
- Research Goals and Targets
- Present Approach and Problems
- What We Would Expect for Space IR Telescopes in 2015-2030
- Role of SPICA
- 今後の課題（高見の個人的コメント）

1. Research Goals and Targets

— Paradigm and Open Questions —



Protoplanetary disk
with gas and dust

What are the distributions of gas, dust, water ice and organic materials: 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?

Formation of cores(?)
Gaseous accretion (?)

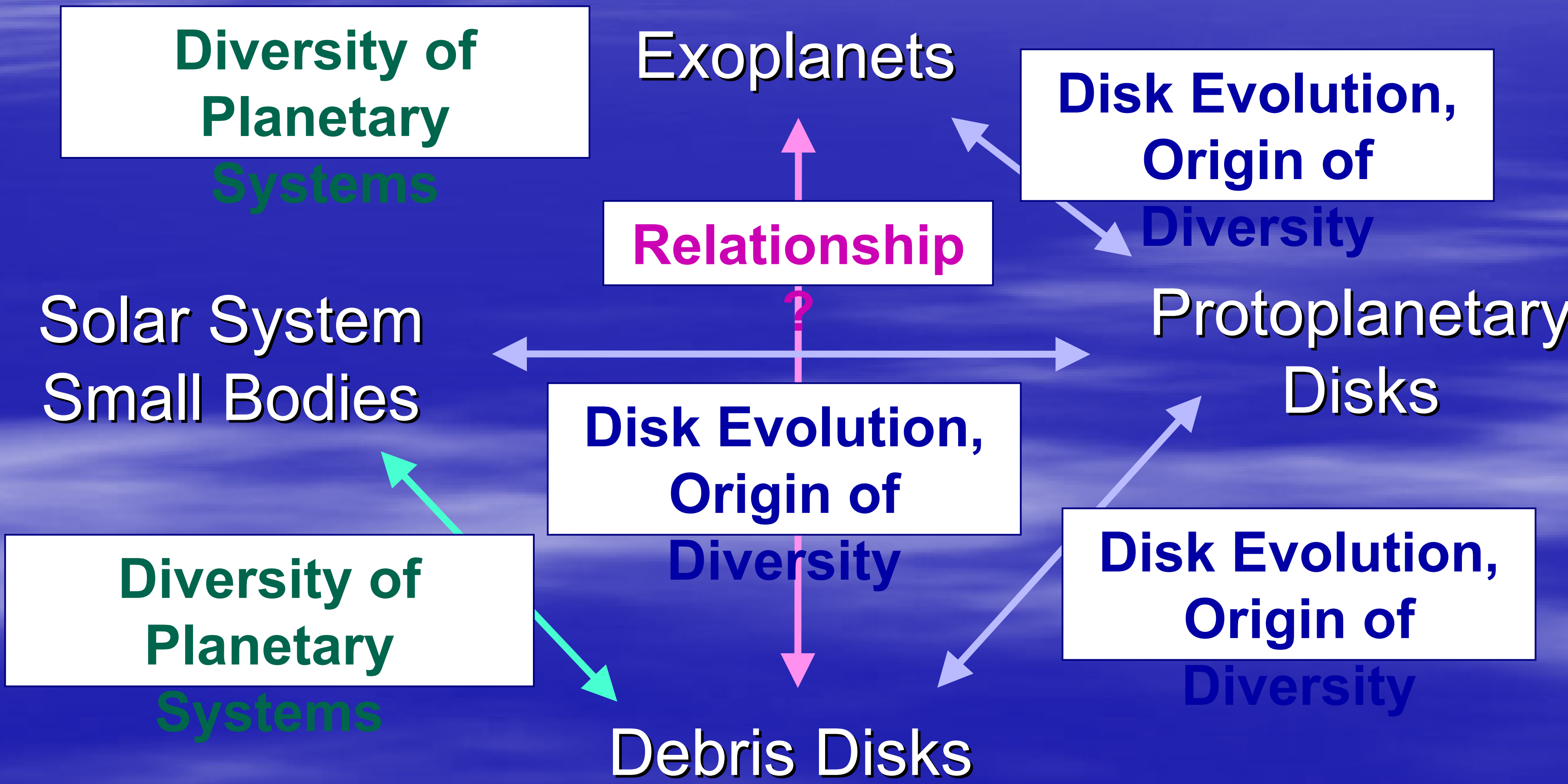
What are the population and diversity of exoplanetary systems?

Planetary systems

Are planetary systems like our solar system common or unique?

1. Research Goals and Targets

— Key Targets —



1. Research Goals and Targets

— Key Targets —

Exoplanets

伊藤さん、成田さん別途講演

Solar System
Small Bodies

大坪さん別途講演

本田さん別途講演

Protoplanetary
Disks

野村さん別途講演

Debris Disks

2. Present Approach and Problems

— Detection and Studies of Exoplanets —

- Radial-Velocity (RV) method
  - More than 300 exoplanets discovered using this method
  - Detection rates biased with the orbital radii, and spectral types (masses) of the parent stars

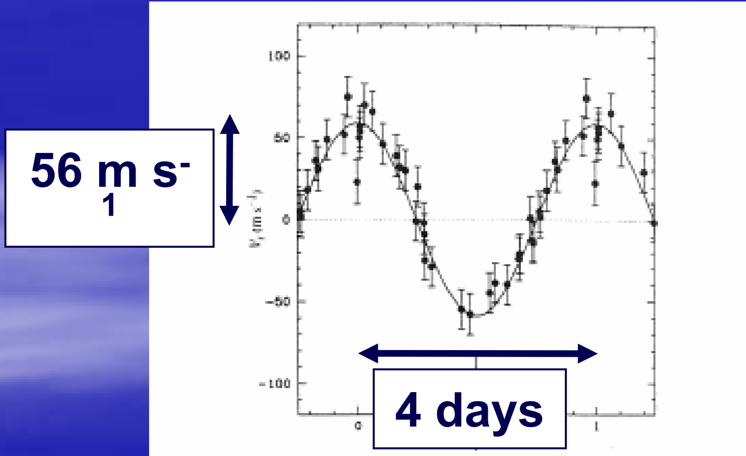
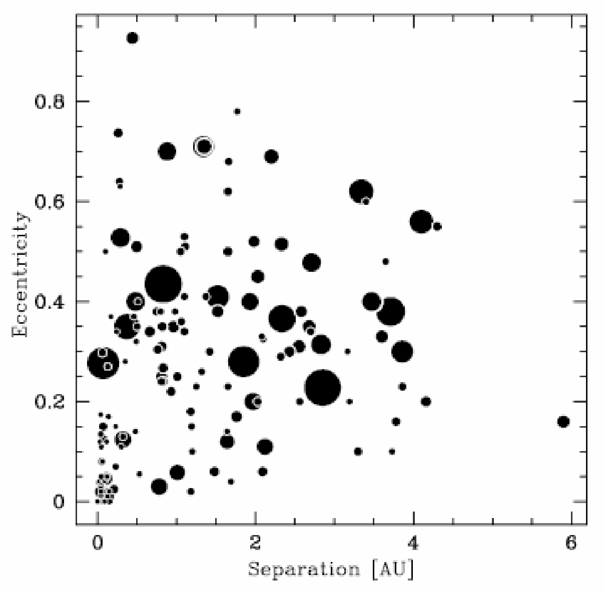


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Mayor & Queloz (1995)

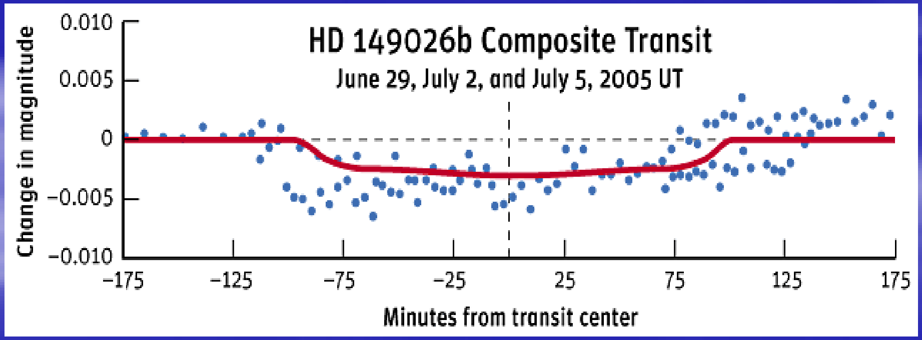


Udry et al. (2007)

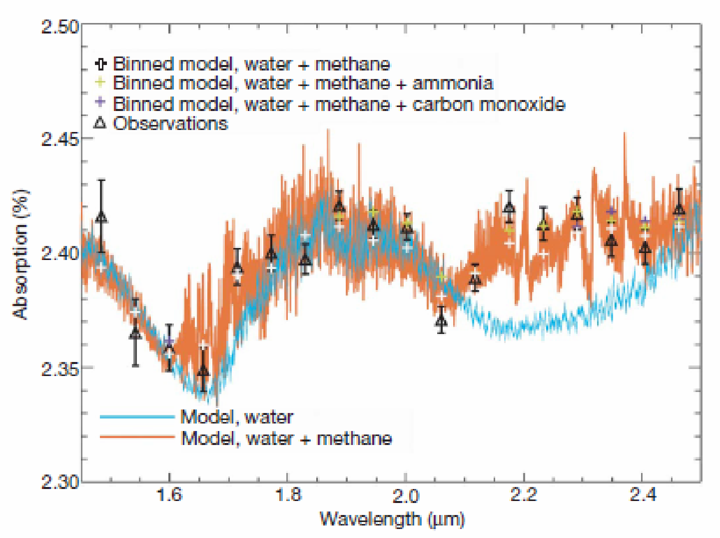
2. Present Approach and Problems

— Detection and Studies of Exoplanets —

- Transiting planets
  - Provide clues for size (thereby core mass), atmospheric temperature and composition
  - Only 10-20 exoplanets have been detected to date
    → the number would dramatically increase by Corot, Kepler etc.



(Sky & Telescope, July 2005)

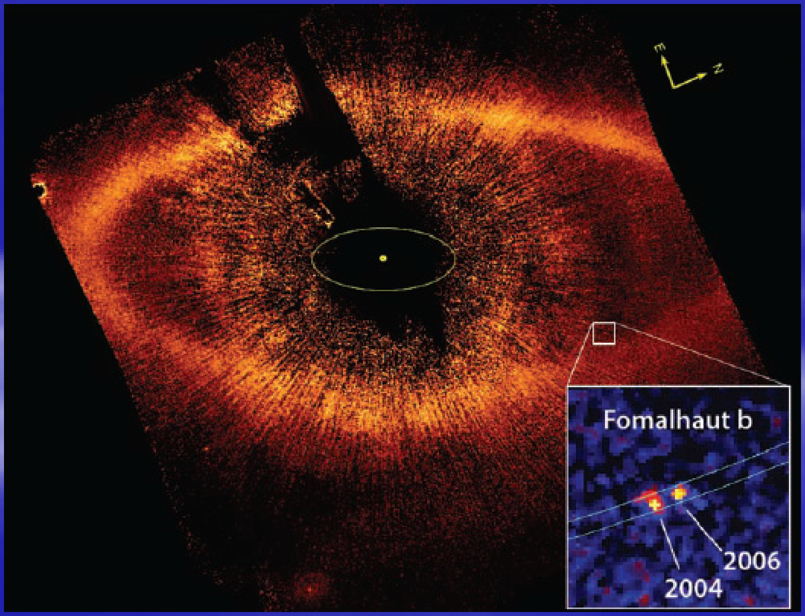


(Swain et al. 2008)

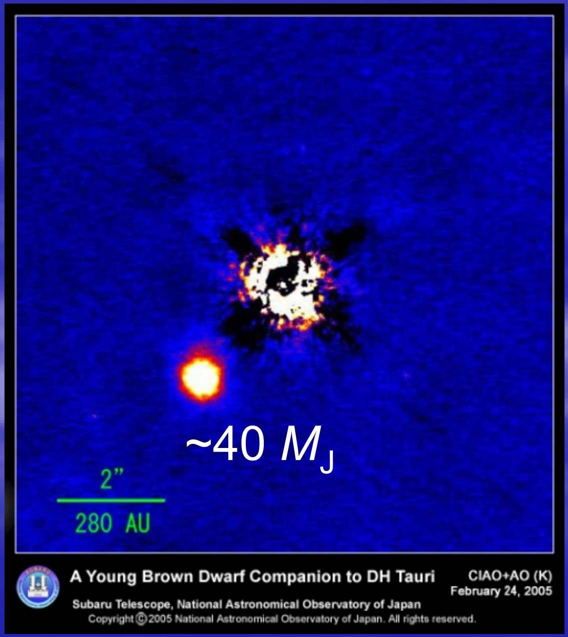
2. Present Approach and Problems

— Detection and Studies of Exoplanets —

- Coronagraphy
  - Has revealed a few candidates of exoplanets, more will be coming soon (e.g., by Subaru-HiCIAO)



(Kalas et al. 2008)



(Itoh et al. 2005)

2. Present Approach and Problems

— Detection and Studies of Exoplanets —

- Coronagraphy
  - Has revealed a few candidates of exoplanets, more will be coming soon (e.g., by Subaru-HiCIAO)
  - Complement the detection by the RV method

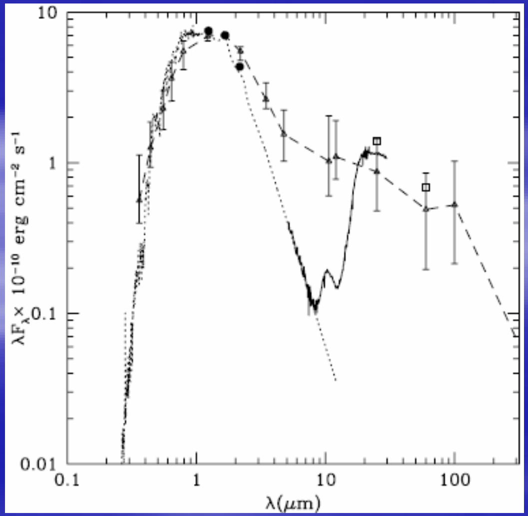
    cf.) applicable for planets with large orbital radii, and stars with any spectral types
  - Would allows us to observe color and spectra, thereby determining mass, atmospheric temperature and composition

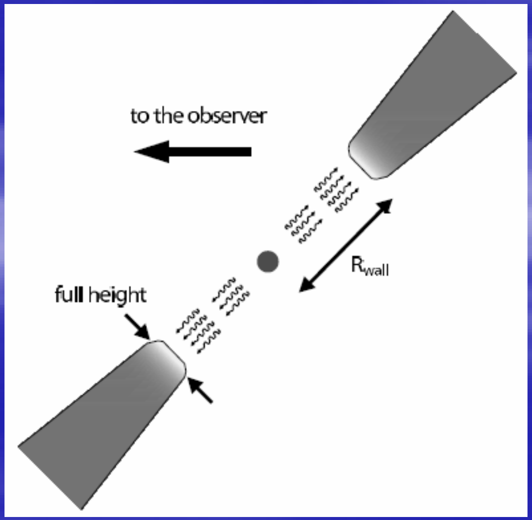
2. Present Approach and Problems

— Protoplanetary Disks —

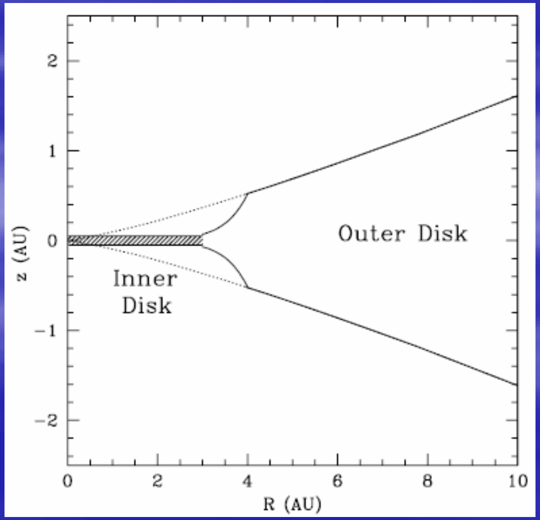
- SEDs
  - Most classical parameters for studying planet forming regions
  - Applied to many targets
  - Large uncertainty due to many modeling parameters

    → Confirmation required





(D'Allesio et al. 2005)

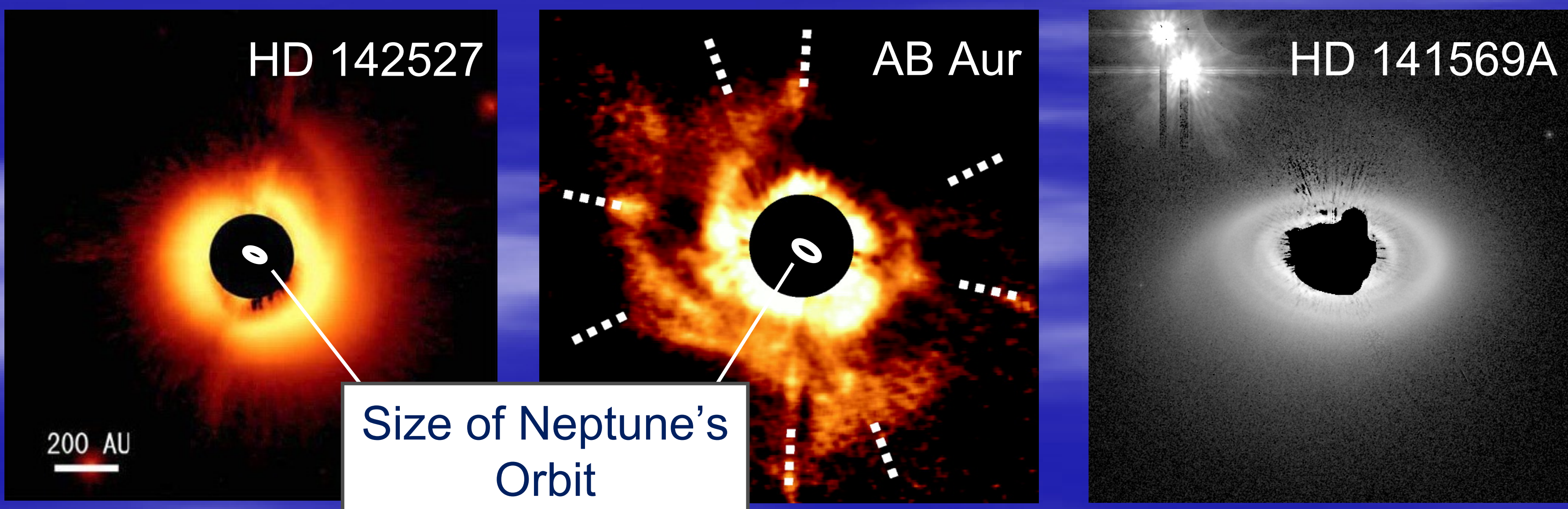


(Calvet et al. 2002)

2. Present Approach and Problems

— Protoplanetary Disks —

- Coronagraphy
  - Reveals detailed disk structures at optical-NIR
  - Applicability limited due to bright stellar continuum (> 30 AU)
  - The number of detection steady increases (cf. HiCIAO)



(Fukagawa et al. 2006) *(Fukagawa et al. 2004)* *(Hubble Site)*

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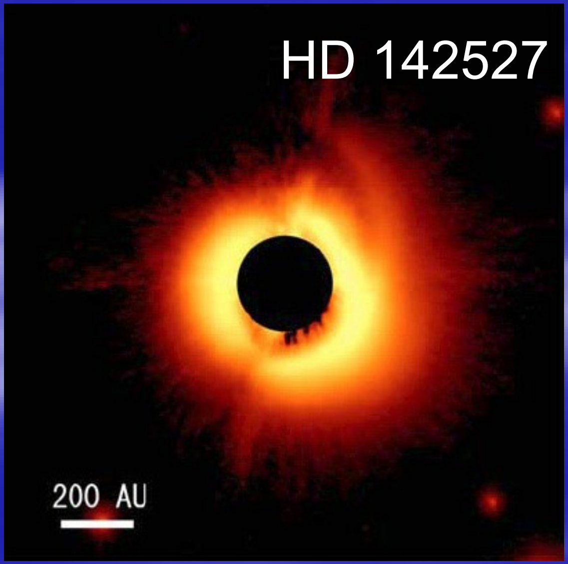
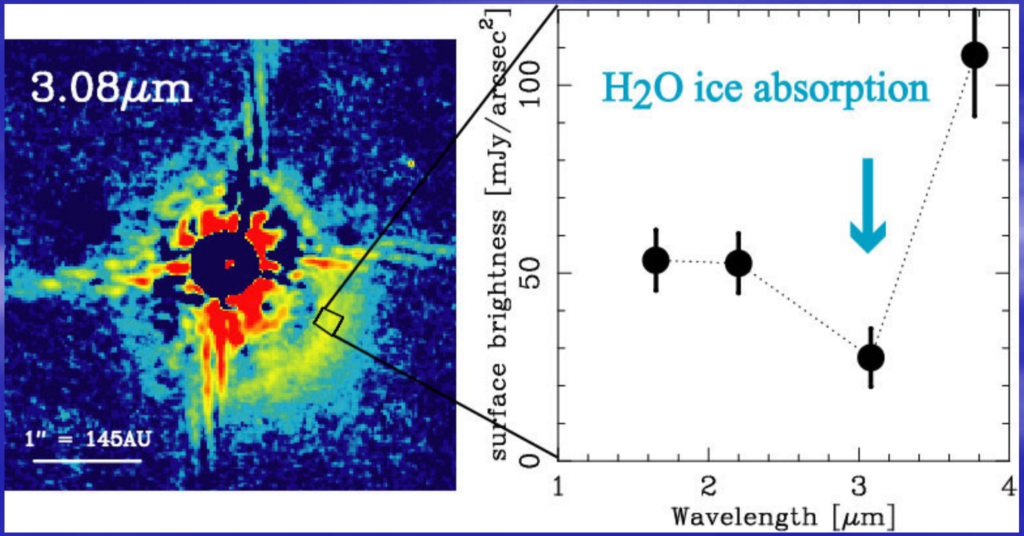


(Fukagawa et al. 2006)

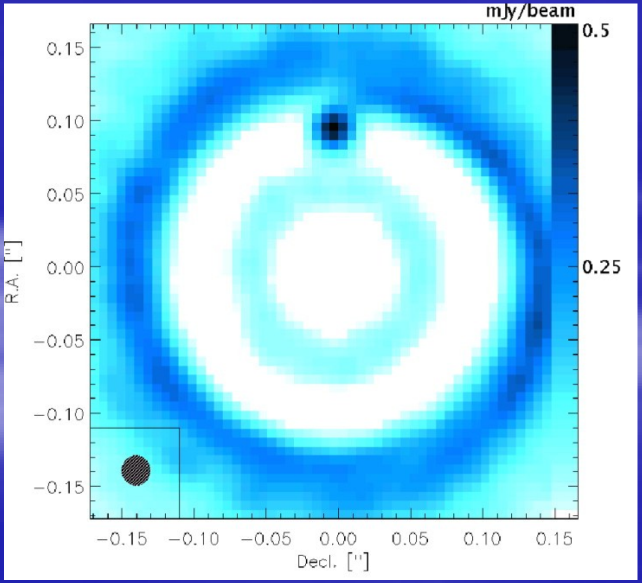


Detection of Ice (Honda et al. 2009)

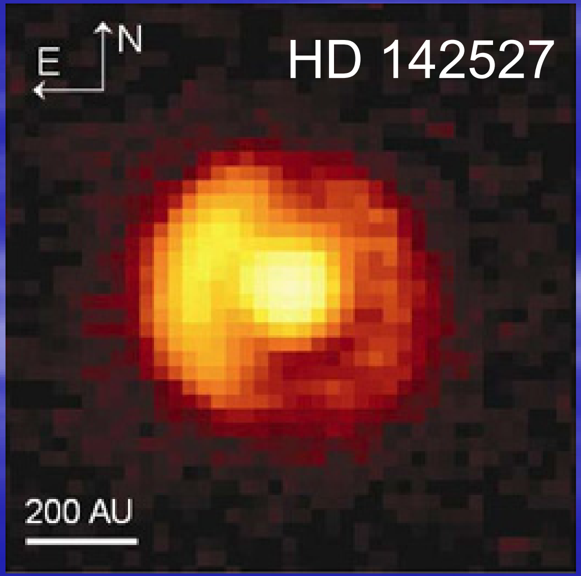
2. Present Approach and Problems

— Protoplanetary Disks —

- Direct Imaging
  - We will see dramatic advance with ALMA, which will allow us to observe optically-thin thermal dust emission at AU scales
  - MIR imaging works in limited cases



Simulated Image for ALMA
(Wolf et al. 2005)

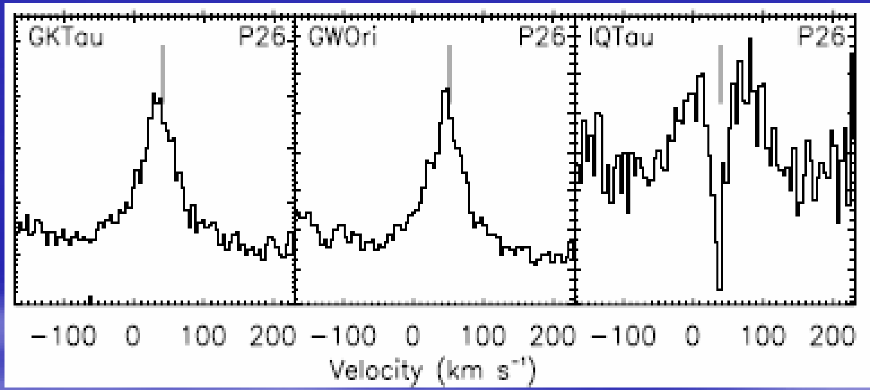


MIR Imaging without coronagraph
(Fujiwara et al. 2006)

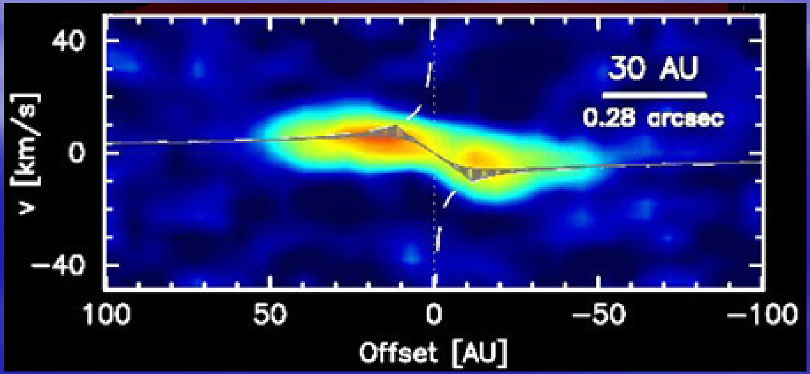
2. Present Approach and Problems

— Protoplanetary Disks —

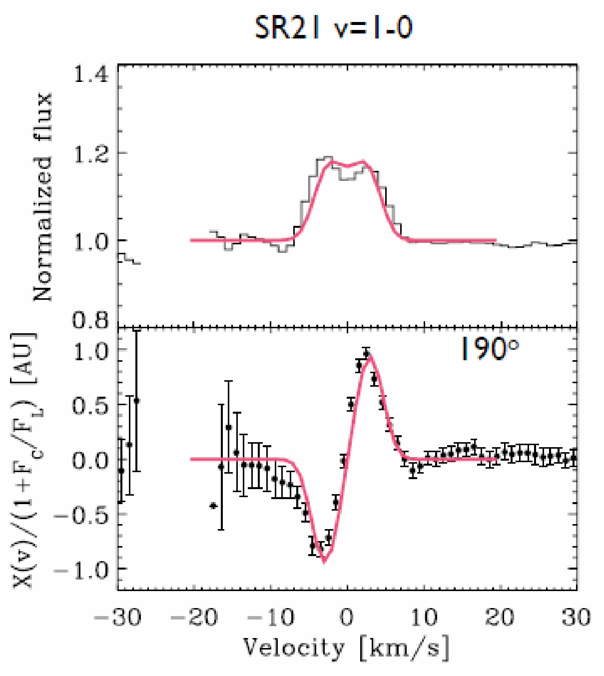
- Spectroscopy (gas)
  - Would allow us to study (1) geometry, (2) physical and chemical conditions, and (3) dissipation timescale of the disks within 30 AU of the star



(Najita et al. 2003)



(Goto et al. 2007)



(Pontoppidan et al. 2008)

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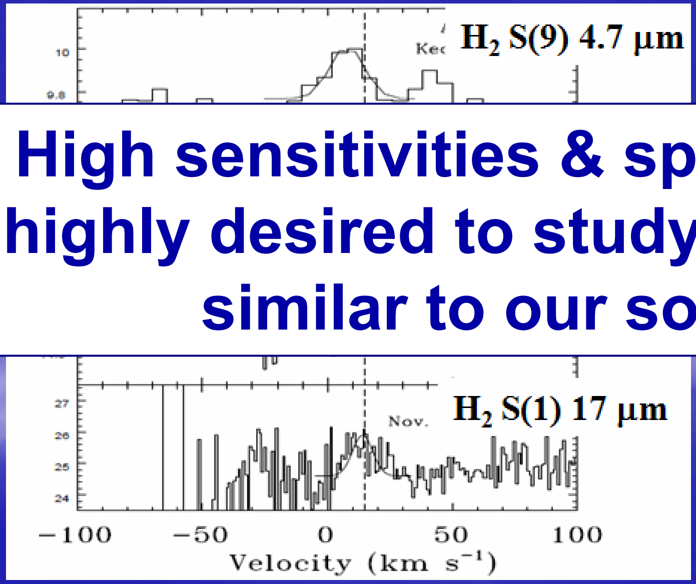
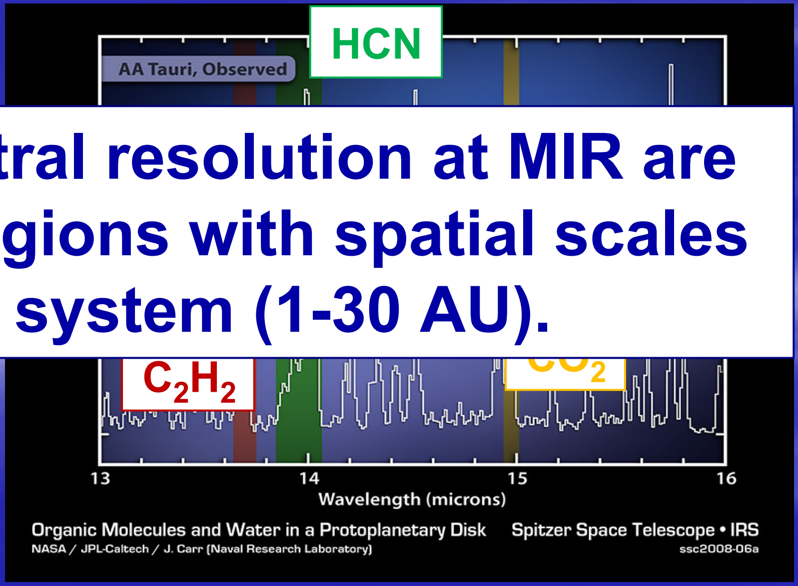




High sensitivities & spectral resolution at MIR are highly desired to study regions with spatial scales similar to our solar system (1-30 AU).

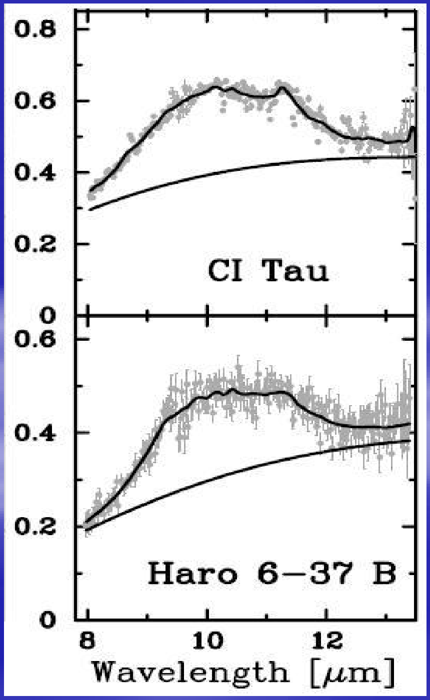
Ground-Based High-Res. Spectroscopy *(Bitner et al. 2008)*

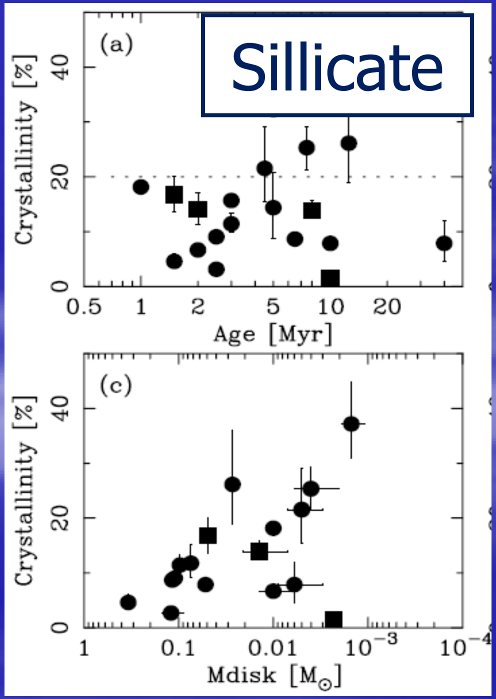
Spitzer Spectra *(Press Release in 2008)*

2. Present Approach and Problems

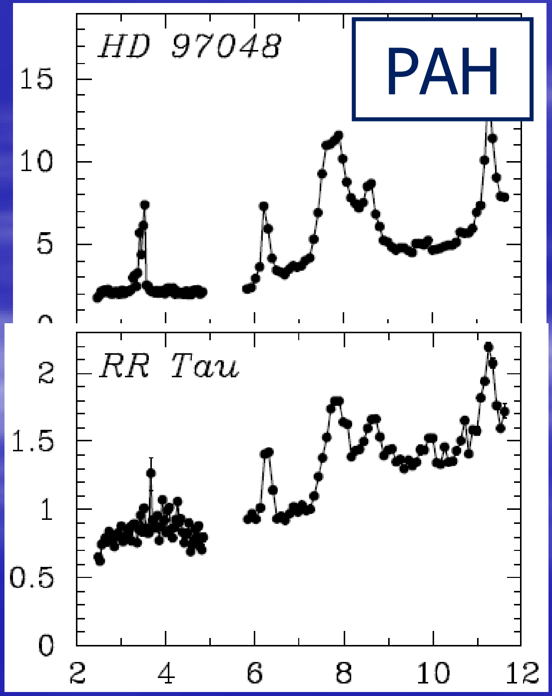
— Protoplanetary Disks —

- Spectroscopy (Dust)
  - Reveals silicate and PAH features on the disk atmosphere
  - Few cases of observations for water ice associated with the disks





(Honda et al. 2006)



(Acke & van de Ancker 2004)

2. Present Approach and Problems

— Protoplanetary Disks —

- Spectroscopy (Dust)
  - Reveals silicate and PAH features on t
  - Few cases of observations for water ice … sks

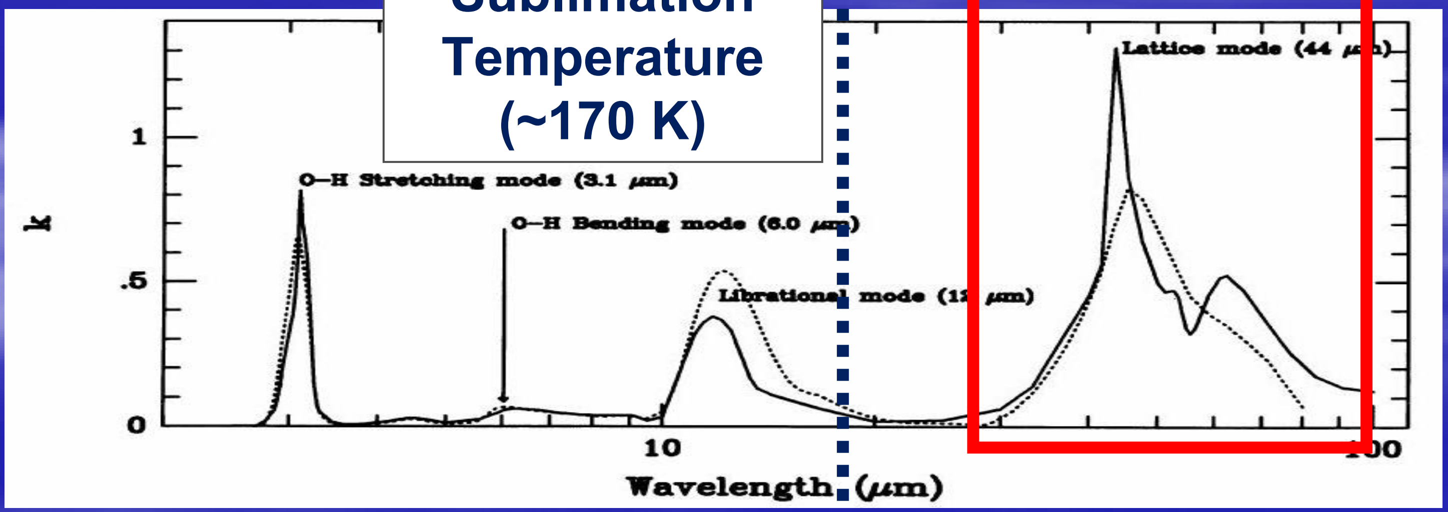
Peak of Black Body

1000 K

300 K

Observable as emission from the disk

Sublimation Temperature (~170 K)



(Smith et al. 1993)

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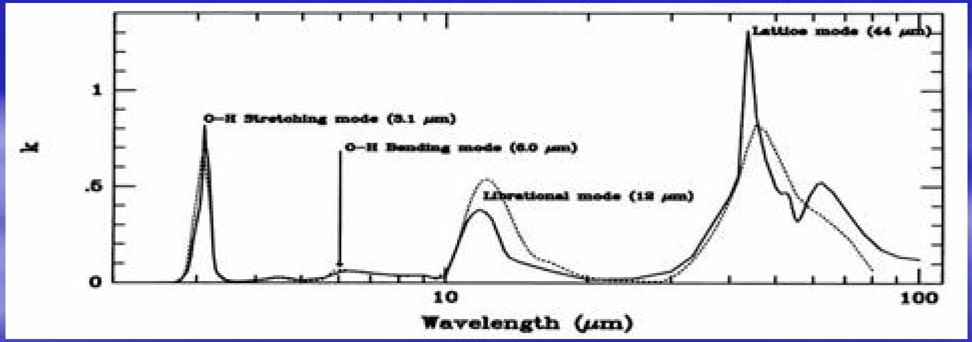
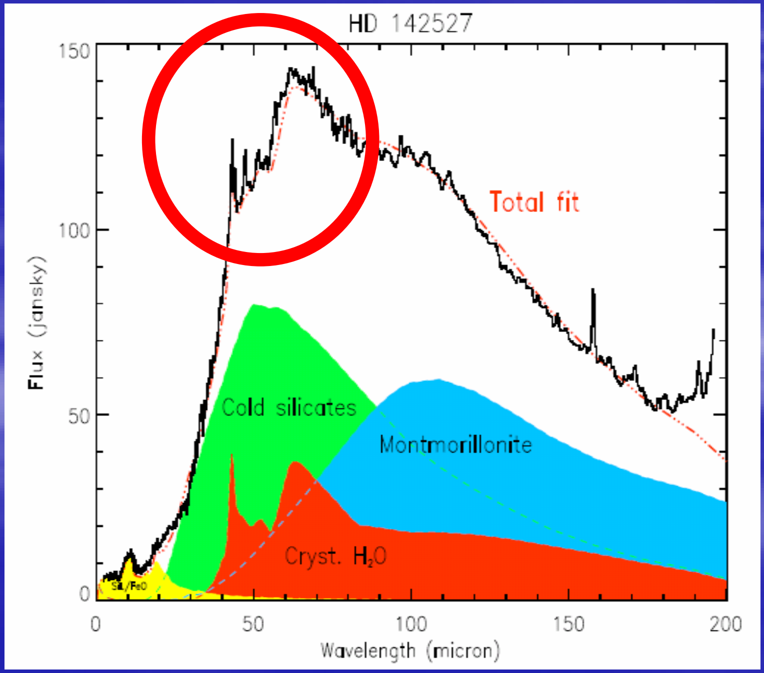




(Malfait et al. 1999)

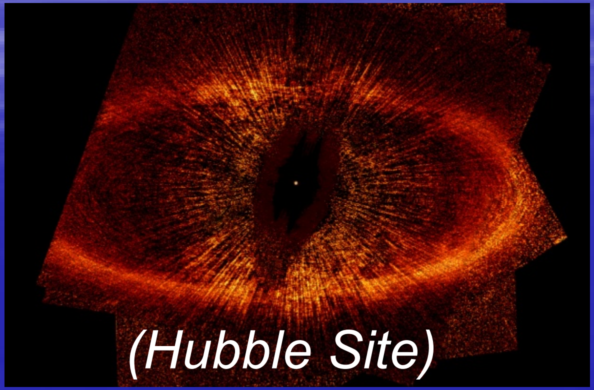
2. Present Approach and Problems

— Debris Disks —

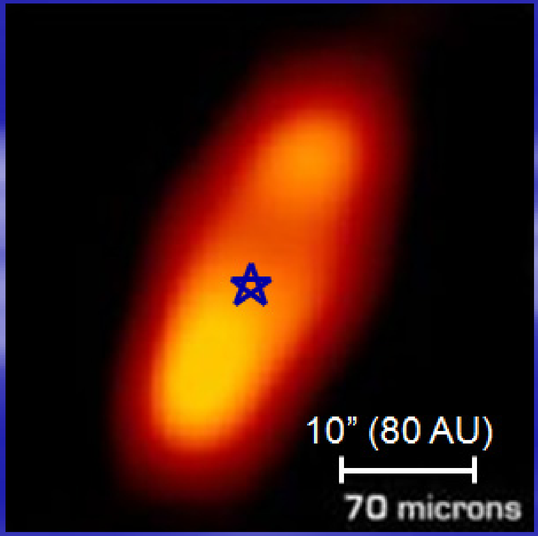
- Photometry at MIR-FIR
  – Has revealed the presence of a number of disks
  – Yet the sensitivity is far from detection for those with masses comparable to the Kuiper belt in our Solar system
- Imaging, Spectro-Imaging, Imaging Polarimetry
  – Intriguing, though so far applied to a very limited number of disks (i.e., nearest and brightest disks)

2. Present Approach and Problems

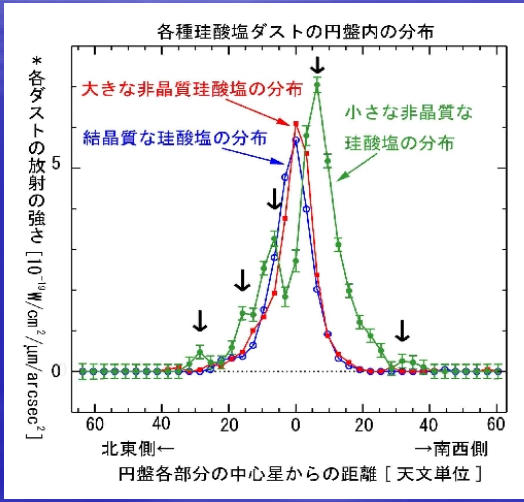
— Debris Disks —

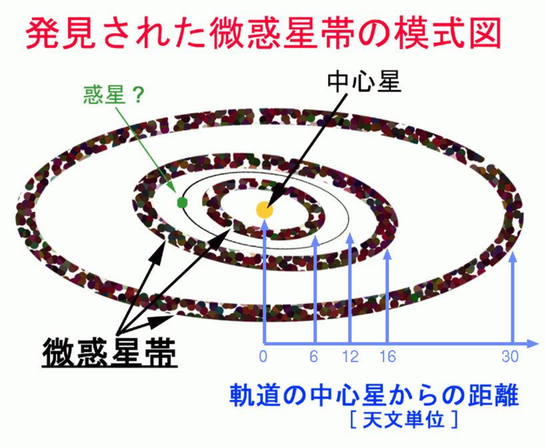


(Hubble Site)

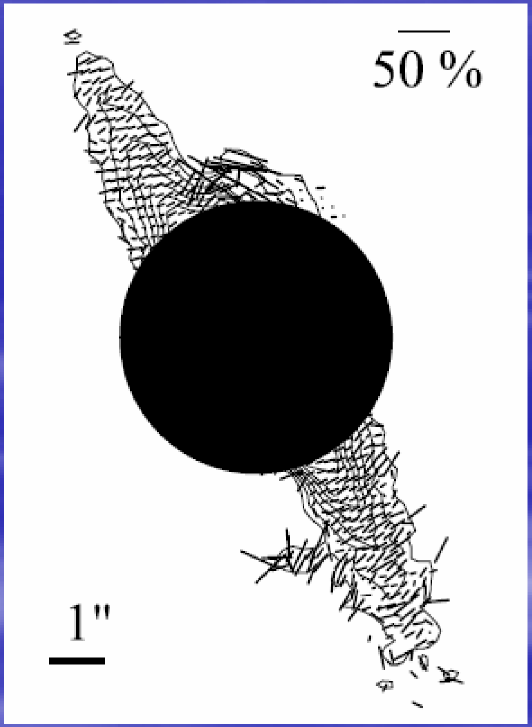


(Spitzer Newsroom)





(Okamoto et al. 2004)

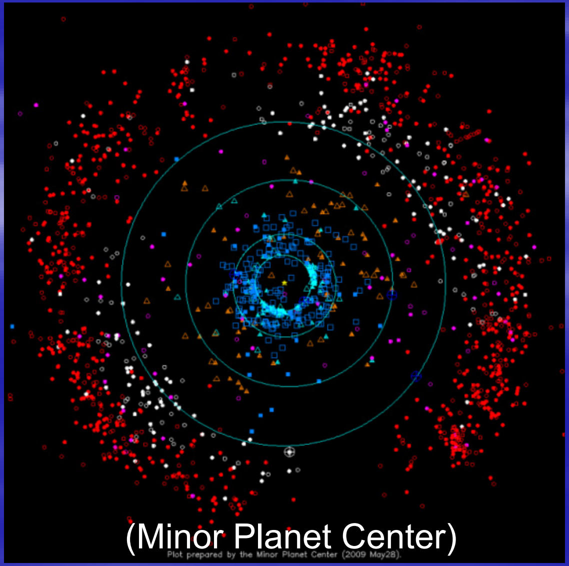


(Tamura et al. 2006)

2. Present Approach and Problems

— Solar System Small Bodies—

- Wide-Field Optical Imaging
  - Revealed >1000 Trans-Neputunian objects (TNOs)
  - Physical properties for most of the TNOs are not well known
- Thermal Imaging, photometry
  - Would allow us to determine the sizes and albedos of TNOs
  - AKARI < 15; Spitzer < 50 objects (detections at several bands are much less)

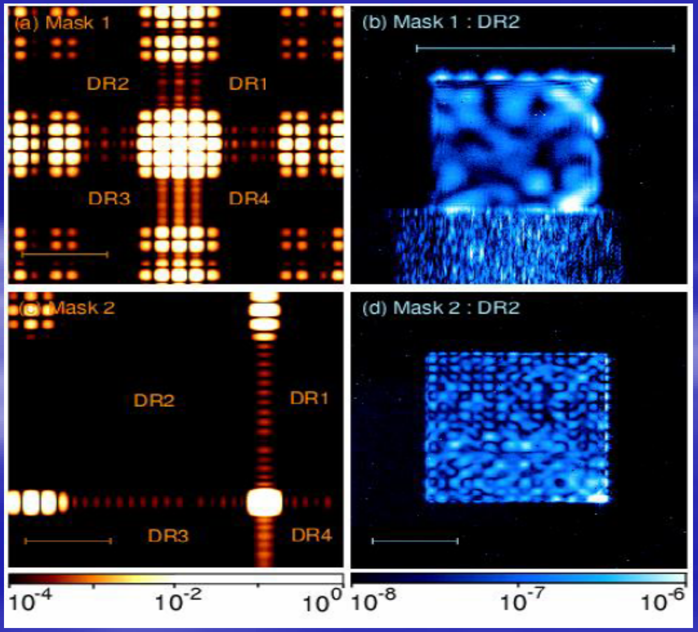


(Minor Planet Center)

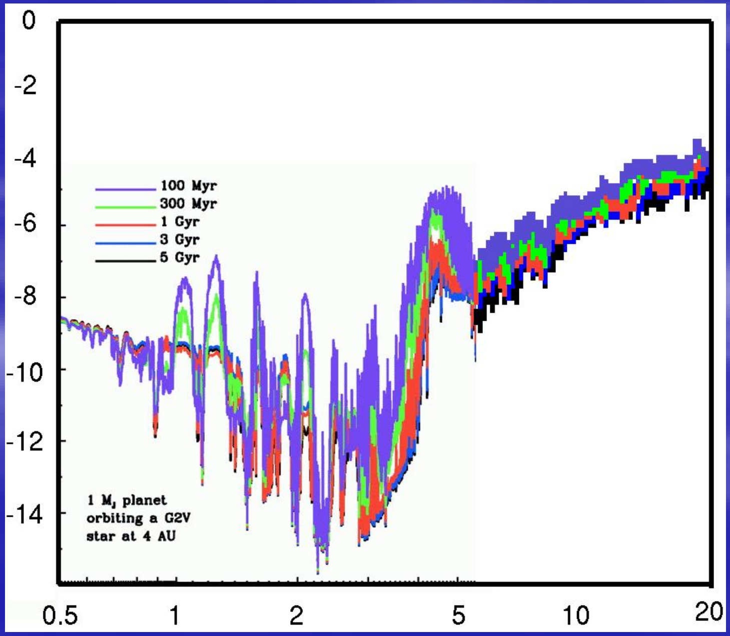
3. What we would expect for Space IR Telescopes in 2015-2030

— Exoplanets —

- Coronagraphy
  - Observations free from speckle noise, and at mid-IR (>3.5 μm), would provide crucial advantages in detection



(Enya et al. 2007)

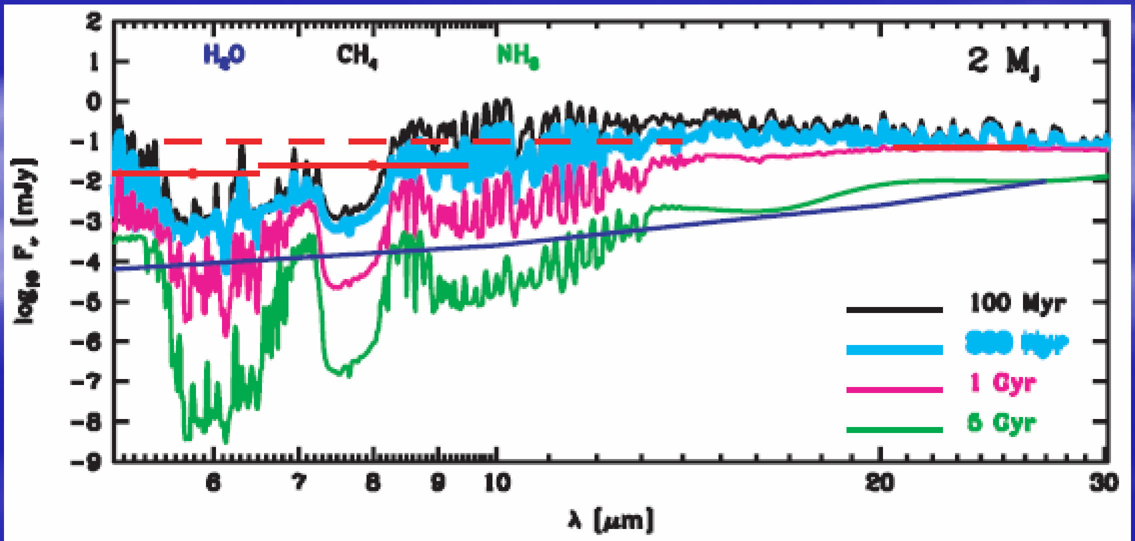


(Burrows et al. 2003)

3. What we would expect for Space IR Telescopes in 2015-2030

— Exoplanets —

- Coronagraphy
  - Observations free from speckle noise, and at mid-IR (>3.5 μm), would provide crucial advantages in detection
  - Observations of molecular bands (H_2O, CH_4, NH_3 etc.) would determine the atmospheric temperature and abundance



(Burrows et al. 2003)

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— Exoplanets —

- Coronagraphy
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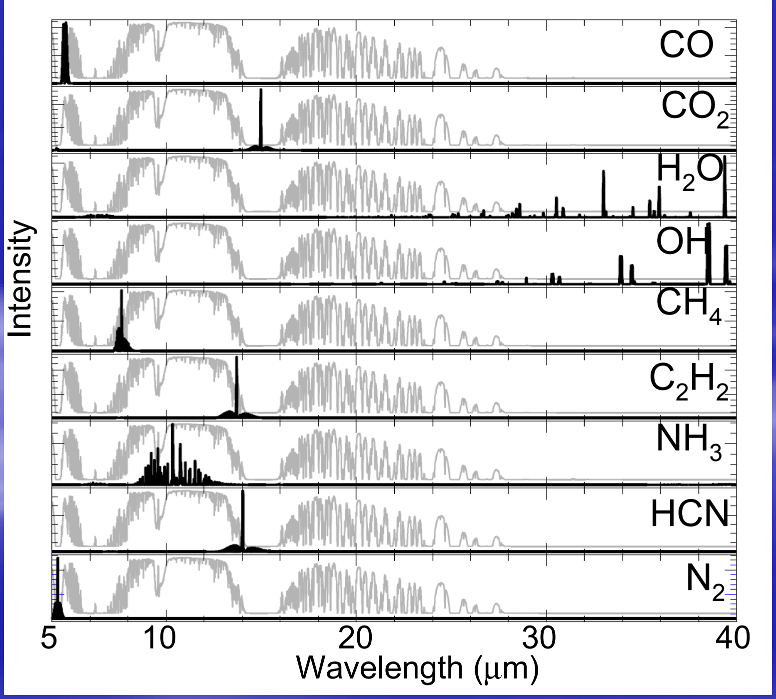
  - Observations of molecular bands (H_2O, CH_4, NH_3 etc.) would determine the atmospheric temperature and abundance
- Observations of Transiting Events
  - Would allow for follow-up observations of newly-discovered planets by TESS, MEarth etc.

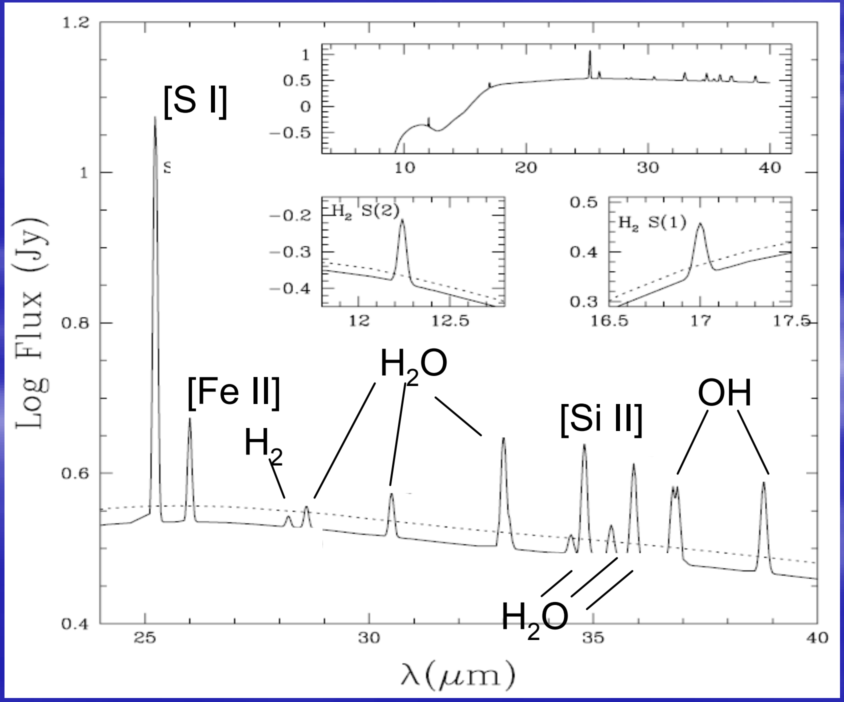
3. What we would expect for Space IR Telescopes in 2015-2030

— Protoplanetary Disks —

- Spectroscopy (gas)
  - Would allow us to observe a variety of emission lines associated with regions at 1-30 AU from the star



(Optically Thin, 1000 K)

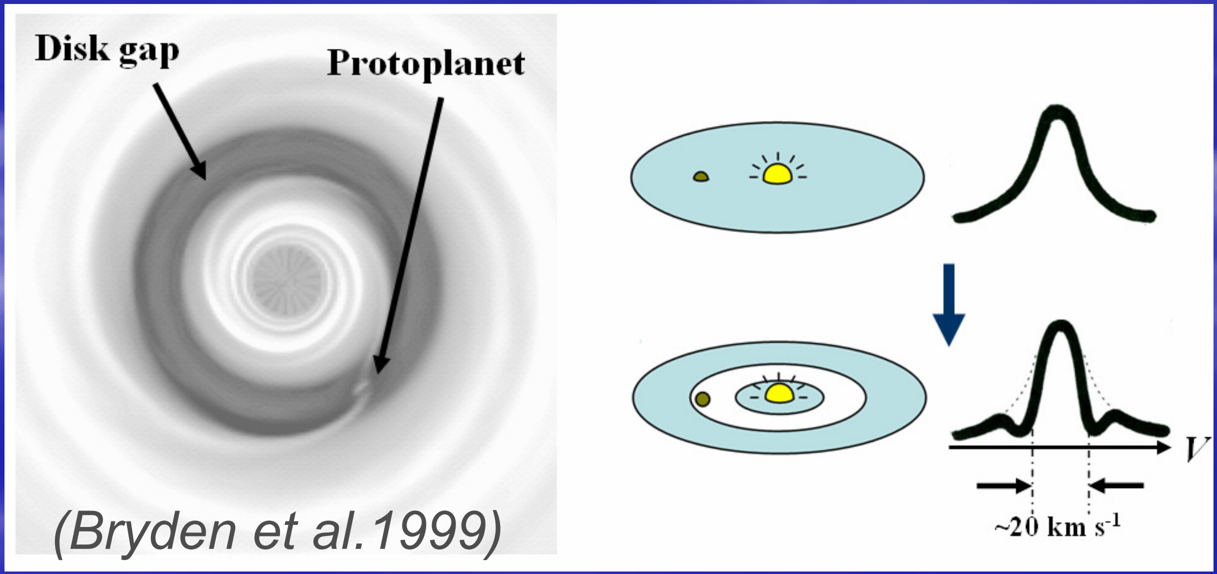


(Gorti & Hollenbach 2004)

3. What we would expect for Space IR Telescopes in 2015-2030

— Protoplanetary Disks —

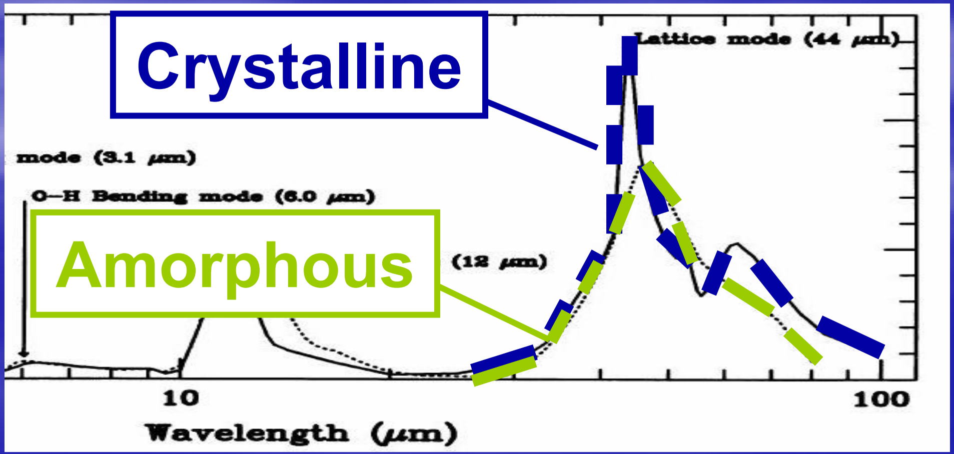
- Spectroscopy (gas)
  - Would allow us to observe a variety of emission lines associated with regions at 1-30 AU from the star
  - Observations of their line profiles would even allow for probing disk evolution due to planet formation



3. What we would expect for Space IR Telescopes in 2015-2030

— Protoplanetary/Debris Disks —

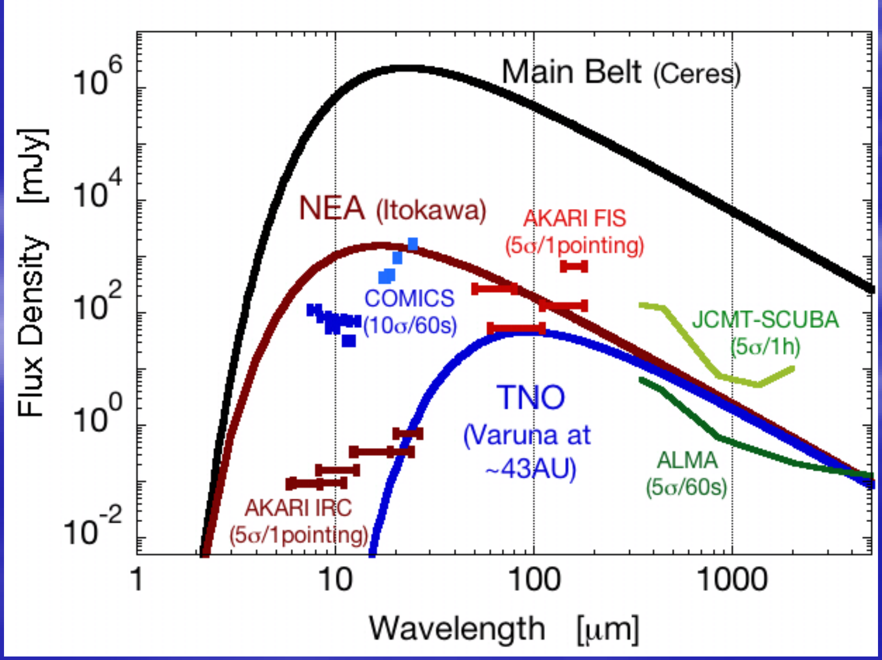
- Photometry, Imaging, Spectro-Imaging
  - High-sensitivity at FIR would allow discoveries of a number of debris disks with masses are comparable to Kuiper belt
  - A combination of high-sensitivity and high angular resolution at MIR-FIR would allow systematic studies of their morphology, distribution of ice and asteroid belts, thereby leading us to understand their evolution and diversity



3. What we would expect for Space IR Telescopes in 2015-2030

— Solar System Small Bodies —

- Photometry, Spectroscopy
  - Photometry at several bands with a wide coverage (30-300 μm) would allow us to measure the accurate SEDs, and derive the size, albedo, and thermal inertia for a significant number of primitive objects in the solar system.



4. Role of SPICA

— Herschel, JWST and SPICA —

- Herschel (3.5-m, 60-672 μm, launched in 2009)
  - PACS (Camera & Spectrograph, 60-210 μm, R=1700)
  - SPIRE (Camera & Spectrograph, 194-672 μm, R=20-1000)
  - HIFI (Spectrometer, 157-625 μm $R=10^3-10^7$)
- JWST (6.5-m, 0.6-29 μm, to be launched in 2013?)
  - NIRCam (Camera, 0.6-5 μm, 2'.2x4'.4)
  - TFI (Spectro-Imager, 1.6-4.9 μm, 2'.2x2'.2, R=100)
  - NIRSpec (Spectrograph, 0.6-5 μm, R=100/1000/2700)
  - MIRI (Camera & Spectrograph, 5-29 μm, R=3000)

4. Role of SPICA

— Herschel, JWST and SPICA —

- SPICA (3.5-m, 4-200 μm, launched in 2017)

Instruments Proposed for SPICA Mission

Instrument	Wavelength (μm)	Performance
MIR Imager (MIRACLE)	4–40	6'×6' FOV + capability of grism spectroscopy
FIR Spectro-Imager (SAFARI)[1]	35–210	2'×2' FOV with R up to ~2000
Far-IR Spectrograph (BLISS)	38–200(430)	R=700
MIR High-Resolution Spectrograph[2]	4–18	$R \sim 3 \times 10^4$
MIR Medium-Resolution Spectrograph	10–40	$R \sim 1 \times 10^3$
Coronagaphic Camera & Spectrograph[3]	3.5–27	dedicated coronagraphy R=20–200 for spectroscopy

[1] Swiny ... shi et al. 2008; [3] Enya et al. 2008

+ NIR Camera

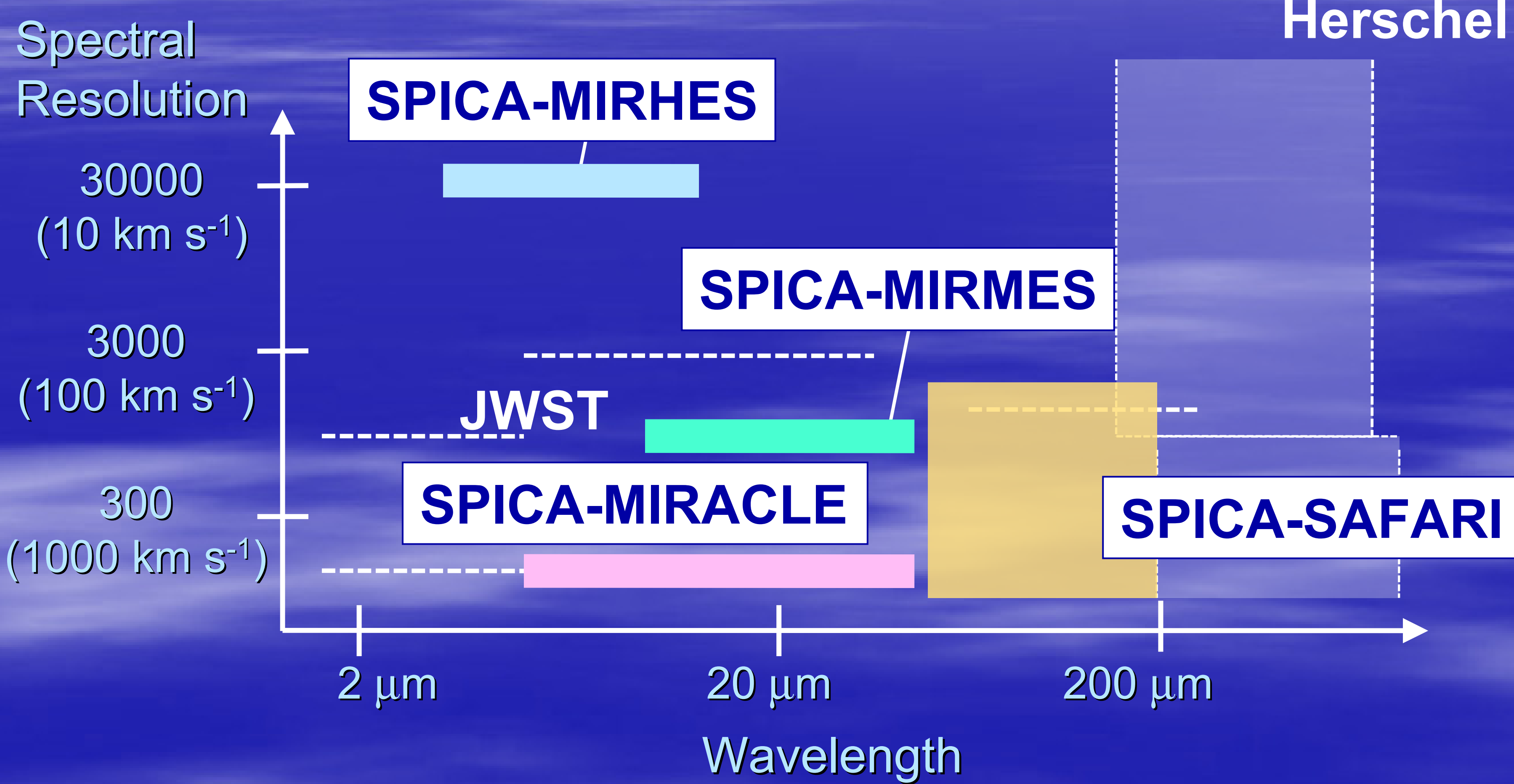
4. Role of SPICA

— Possible Advantages of SPICA —

- Overwhelming Sensitivity at 20-200 μm
  (MIRACLE, MIRMES, SAFARI, BLISS)
- Capability of Spectro-Imaging at 40-200 μm
  (SAFARI)
- Overwhelming Spectral Resolution at 8-18 μm
  (MIRHES)
- High-Contrast Coronagraphy & Its Capability of Spectroscopy
  (Coronagraph Camera & Spectrograph)

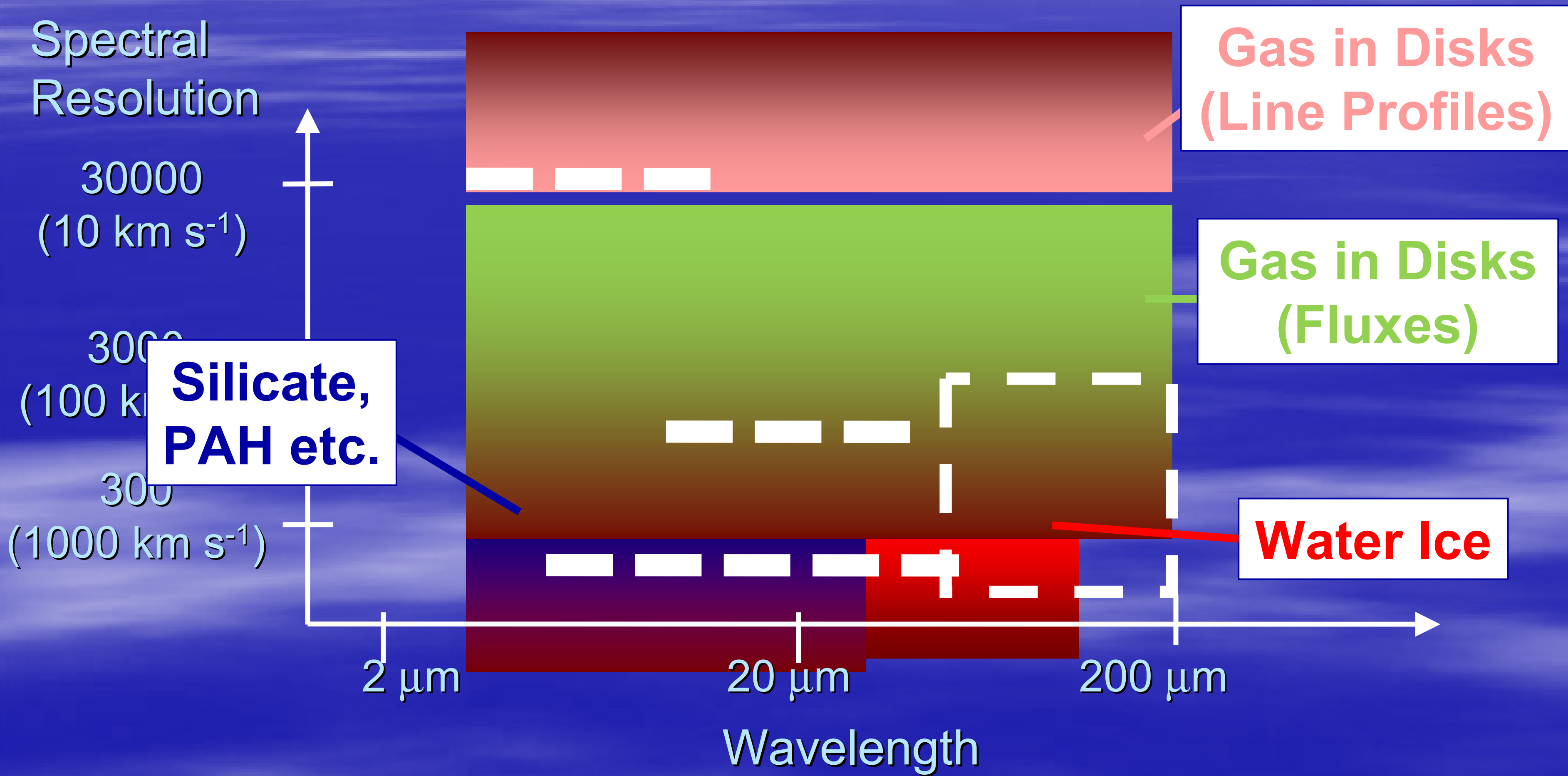
4. Role of SPICA

— Spectroscopic Capability —



4. Role of SPICA

— Spectroscopic Capability —



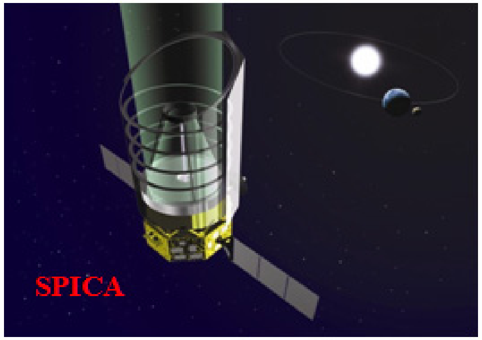
Proposed Goals of the SPICA Mission
(from Mission Requirement Document)

= Summary of This Talk

Major Objective [3]

惑星系形成過程の総合理解

-Thorough Understanding of
Planetary System Formation-



Planetary Systems : Objective #1

- 科学目的 Purpose
  - 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

Planetary Systems : Objective #2

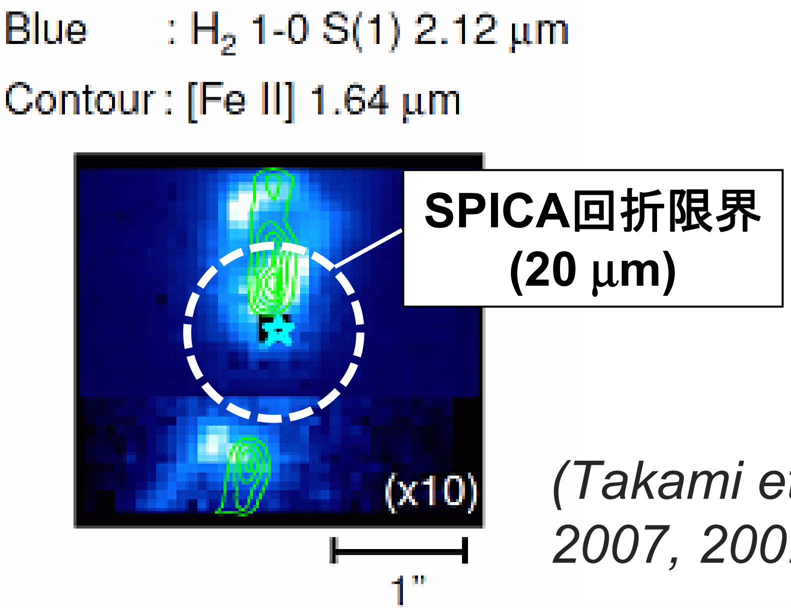
- 科学目的 Purpose
  - 原始惑星系円盤のガスの散逸過程および散逸時間スケールを観測し、木星型惑星の形成メカニズム、および地球型惑星の生成条件を明らかにする。
    - We reveal the formation mechanism of gas giant planets and initial condition of terrestrial planet formation, by observing the process and timescale of dispersing gas in protoplanetary disks
- 科学目標 Target
  - 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

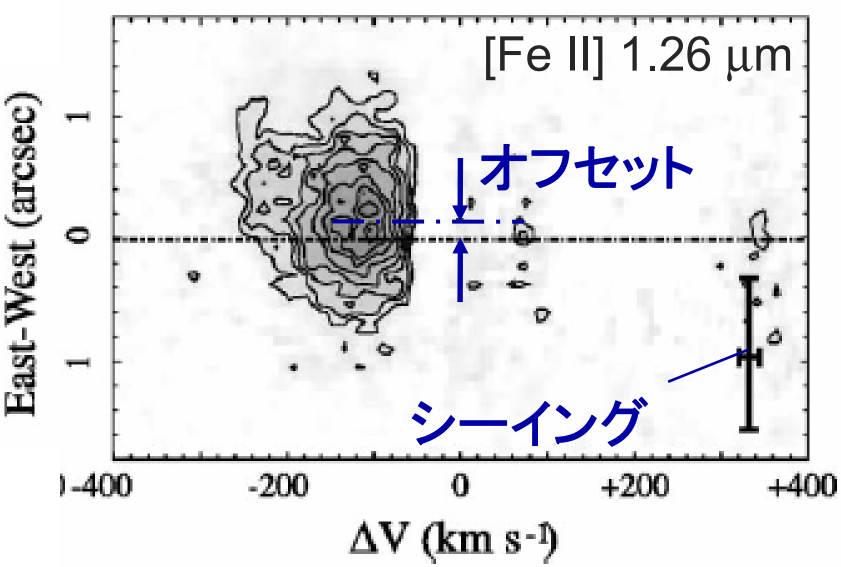
Planetary Systems : Objective #2

- 科学目的 Purpose
  - 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。

H_2 輝線、禁制線はジェット・ウィンドからの放射の混入が大きな問題になりうる。（ある程度の空間サンプリングがあれば、円盤に付随する放射かどうかは判定可能。）



(Takami et al. 2007, 2002)



Planetary Systems : Objective #3

- 科学目的 Purpose
  - 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

Planetary Systems : Objective #4

- 科学目的 Purpose
  - 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・低分散分光装置　MIRACLE~~
~~中間赤外コロナグラフ　SCI~~
遠赤外線分光撮像装置　SAFARI

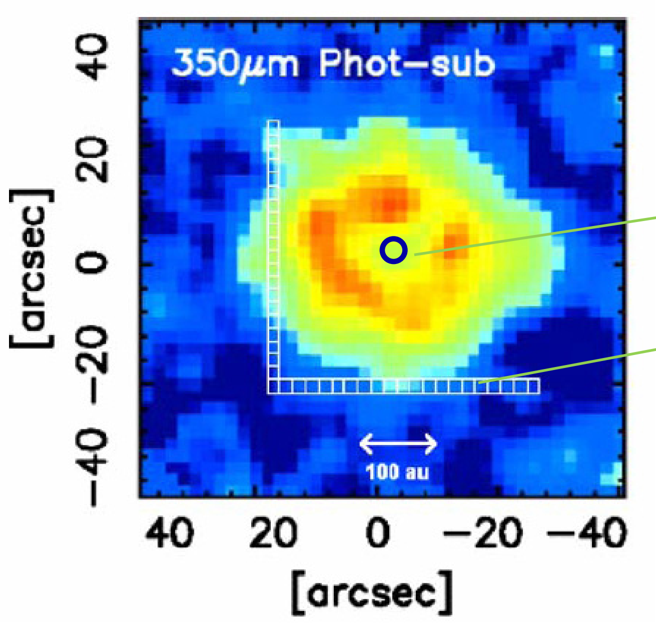
Planetary Systems : Objective #5

- 科学目的 Purpose
  - 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・低分散分光装置 MIRACLE

遠赤外線分光撮像装置 SAFARI



スノーライン

SPICAの空間分解能@40-60 μm

(Swinyard et al. 2008)

- 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・低分散分光装置 MIRACLE

遠赤外線分光撮像装置 SAFARI

Planetary Systems : Objective #6

- **科学目的 Purpose**
  - 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

ここで、皆さんに審査していただきます。

- 目標設定に重大な問題があるか？
  あるいはこれらは妥当であり、国際的にも競争力のあるテーマか？
- 現在提案されている装置の仕様は、これらのサイエンスに適したものであるか？
  もしそうでないとしたら、仕様をどのように改善すべきか？
- 抜け落ちている重要なObjectiveがあるか？もしあるなら
  - 現在提案されている装置で実行できるか？
  - 現在記述されているものに比べて、優先順位の高いものか？

今後の課題
（高見の個人的コメント）

- 原始惑星系円盤の固体フィーチャーのサイエンスケースをどう強化するか
  - 生命系や有機物に関係する研究提案を強化できないか？
- 多波長にわたる統一レガシープログラムを作れないか？

統一レガシープログラム素案
（原始惑星系円盤）

- **HiCIAO-SEEDs (2009-2014)**
  - >10-30 AU の、ダスト円盤の表面の構造を観測

- **ひとつの観測装置、ひとつの望遠鏡で全てを理解するのは不可能→多角的観測が必要**
- **複数望遠鏡によるレガシープログラムをあらかじめ提案してしまうことにより、SPICA以外の望遠鏡（すばる、ALMA、TMT）の観測時間を獲得するのにも有利（？）**

- **TMT (20??-)**
  - 現在の地上観測（高分散分光、コロナグラフ観測）をさらに高い精度、そして多数のサンプルで展開

今後の課題
（高見の個人的コメント）

- 原始惑星系円盤の固体フィーチャーのサイエンスケースをどう強化するか
  - 生命系や有機物に関係する研究提案を強化できないか？
- 多波長にわたる統一レガシープログラムを作れないか？
- 搭載される装置の制限から、実際にはこのような百花繚乱な話にはならない。実際に搭載される装置次第では、強調する部分を大幅に変更する必要あり。