The next-generation
Infrared astronomy mission

SPICA

Space Infrared Telescope for Cosmology and Astrophysics

Review of MRD

Resolution of Birth and Evolution of Galaxies

1-2 June 2009 SPICA Science Workshop 2009
@ Univ. Tokyo

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On behalf of SPICA Extragalactic Science team

JAXA esa

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Contents

- Research Goals & Targets
  - Open questions in 2017-20, after Herschel, ALMA & JWST?
  - Introduction to other speakers in this session
- Description of Scientific Targets
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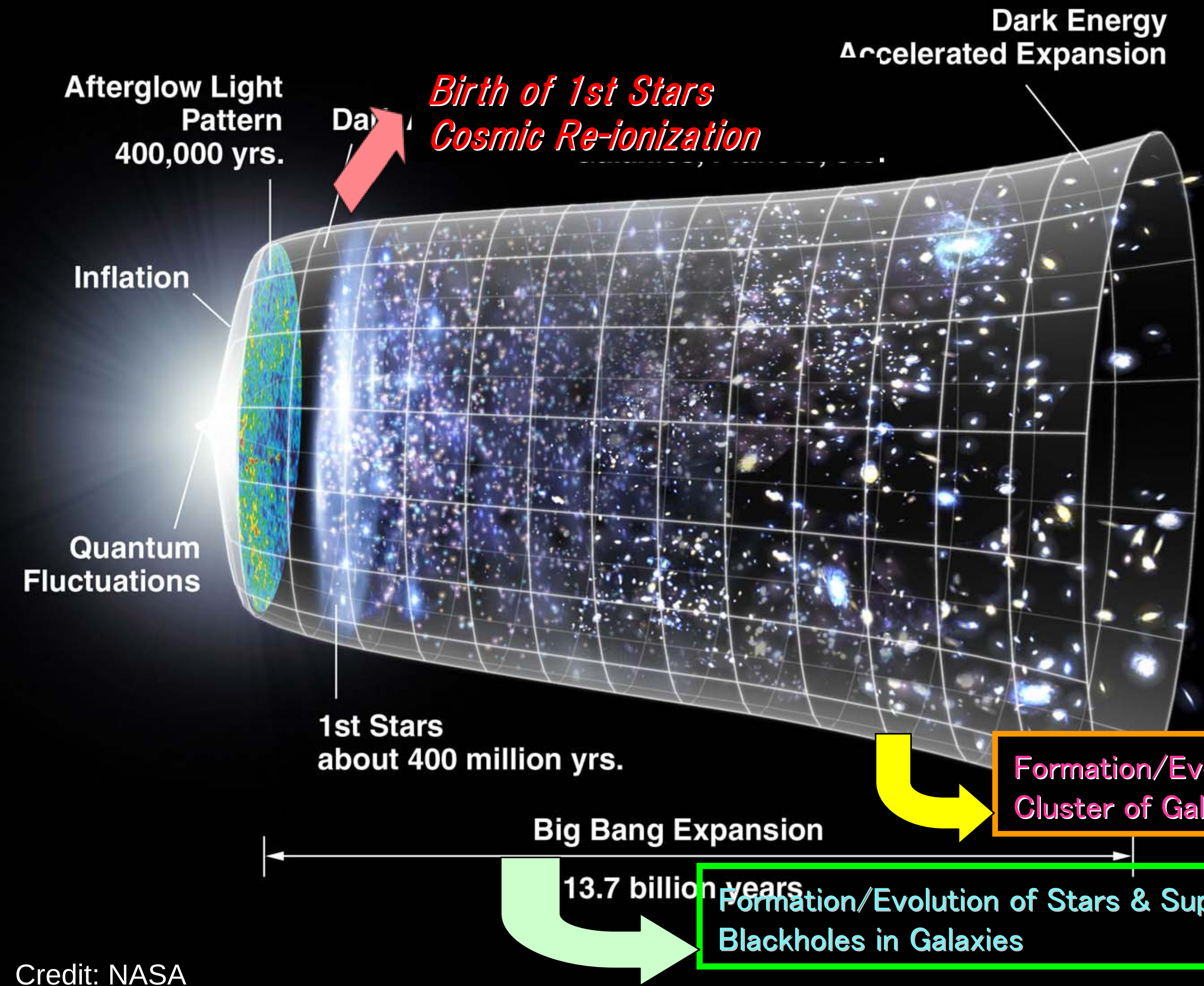
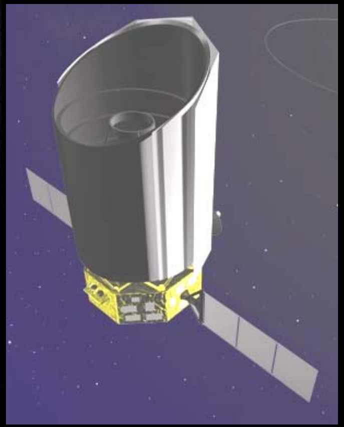
- Role of SPICA
  - Role of SPICA for study of distant universe
  - problems to be solved in short term

Resolution of Birth and Evolution of Galaxies



SPICA



Credit: NASA

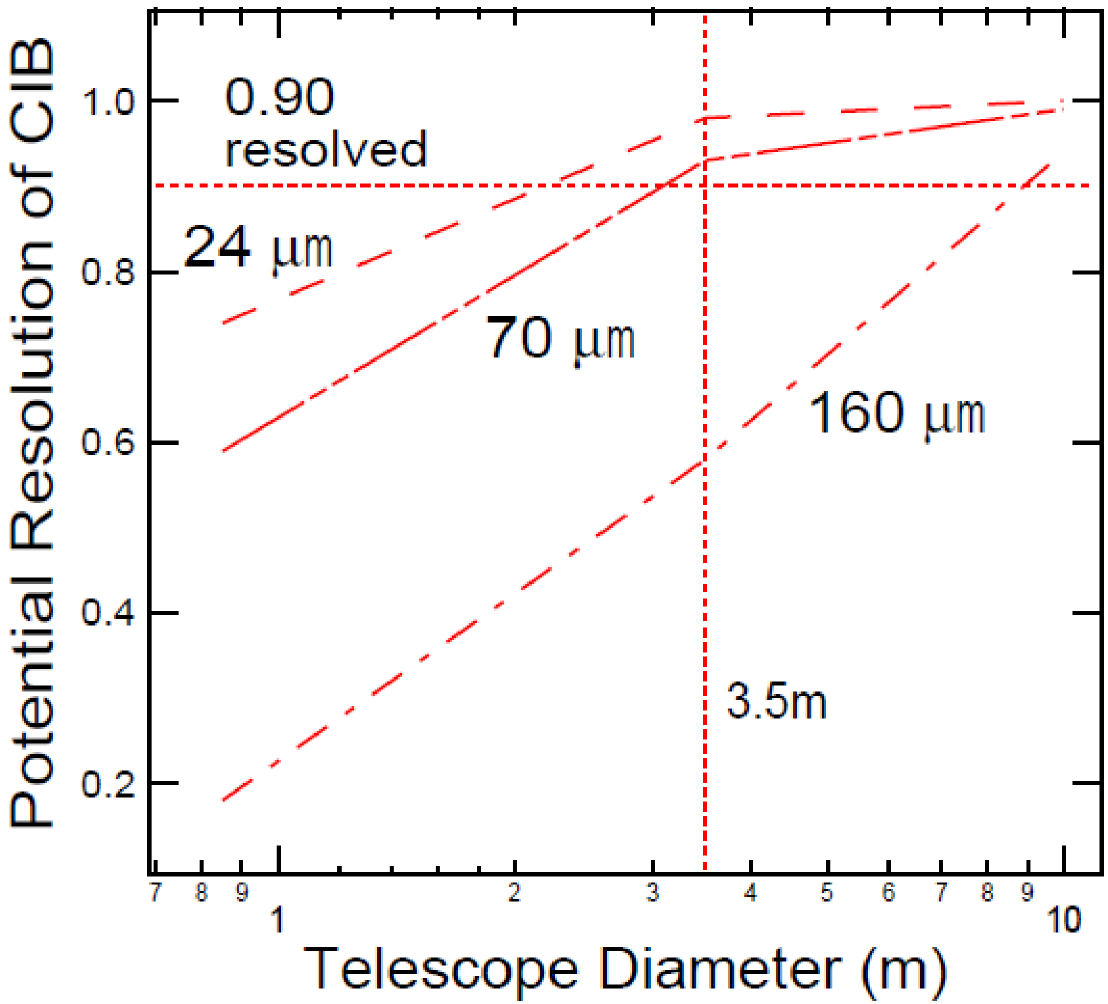
Herschel launched !!!

14 May 2009

- Deep FIR imaging :
  - 3.5m aperture : confusion limit substantially improved but very limited cosmic volume
- FIR & Submm spectroscopy – still limited to $z<<1$

Credit: ESA

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)

*Herschel requires **(a few) hour** to reach the confusion limit at 70-100µm*

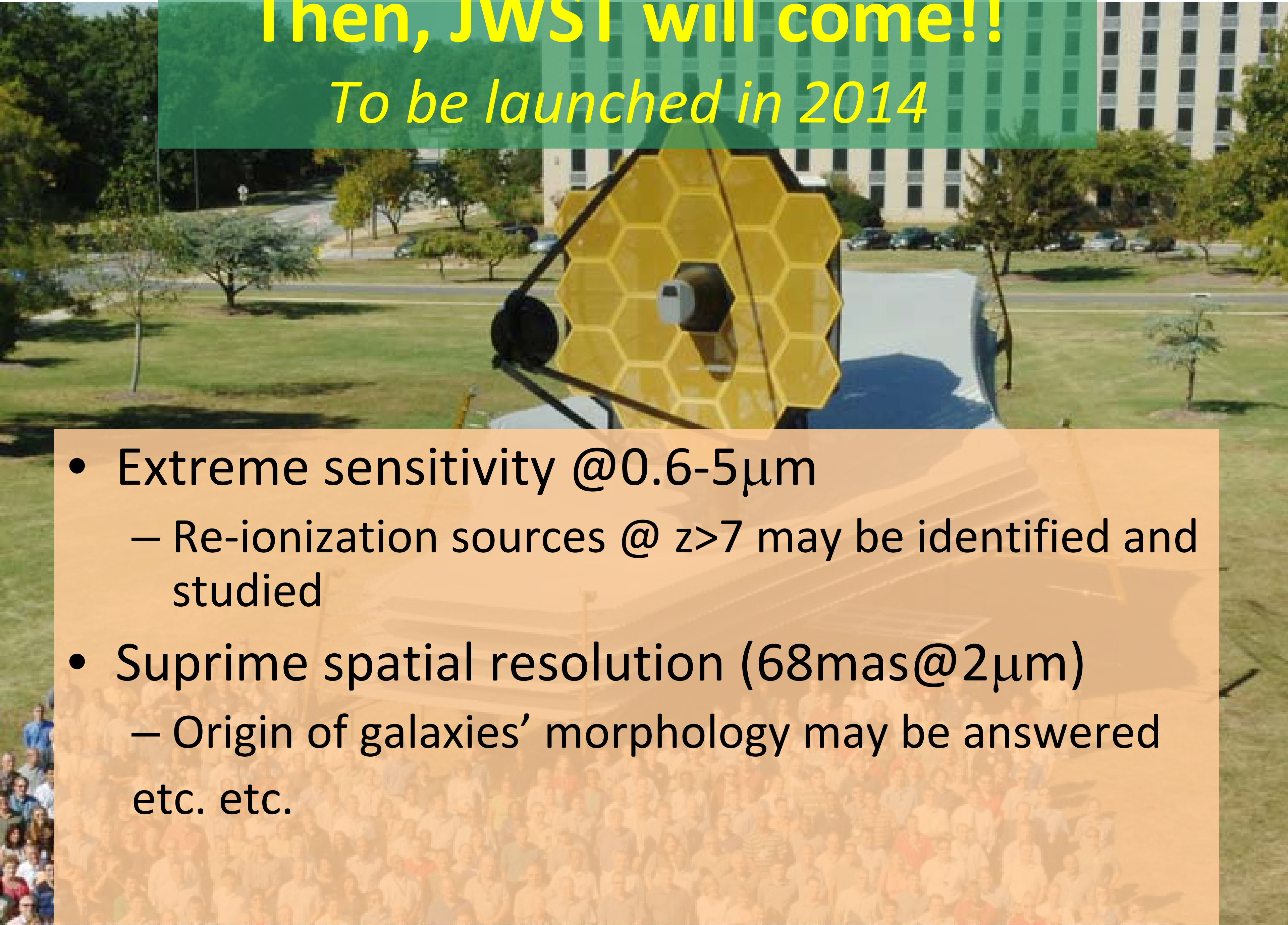
ALMA will be available soon

commission from 2012

- Overwhelming spatial resolution in the submm
- Star-forming galaxies with SFR~100 Mo/yr @ z>3 will be studied, though survey area may be limited to a few 100 arcmin^2 (since FOV~20")
- coordination with LMT CCAT may give information on for unbiased sample of z>3 submm galaxies

Then, JWST will come!!

To be launched in 2014

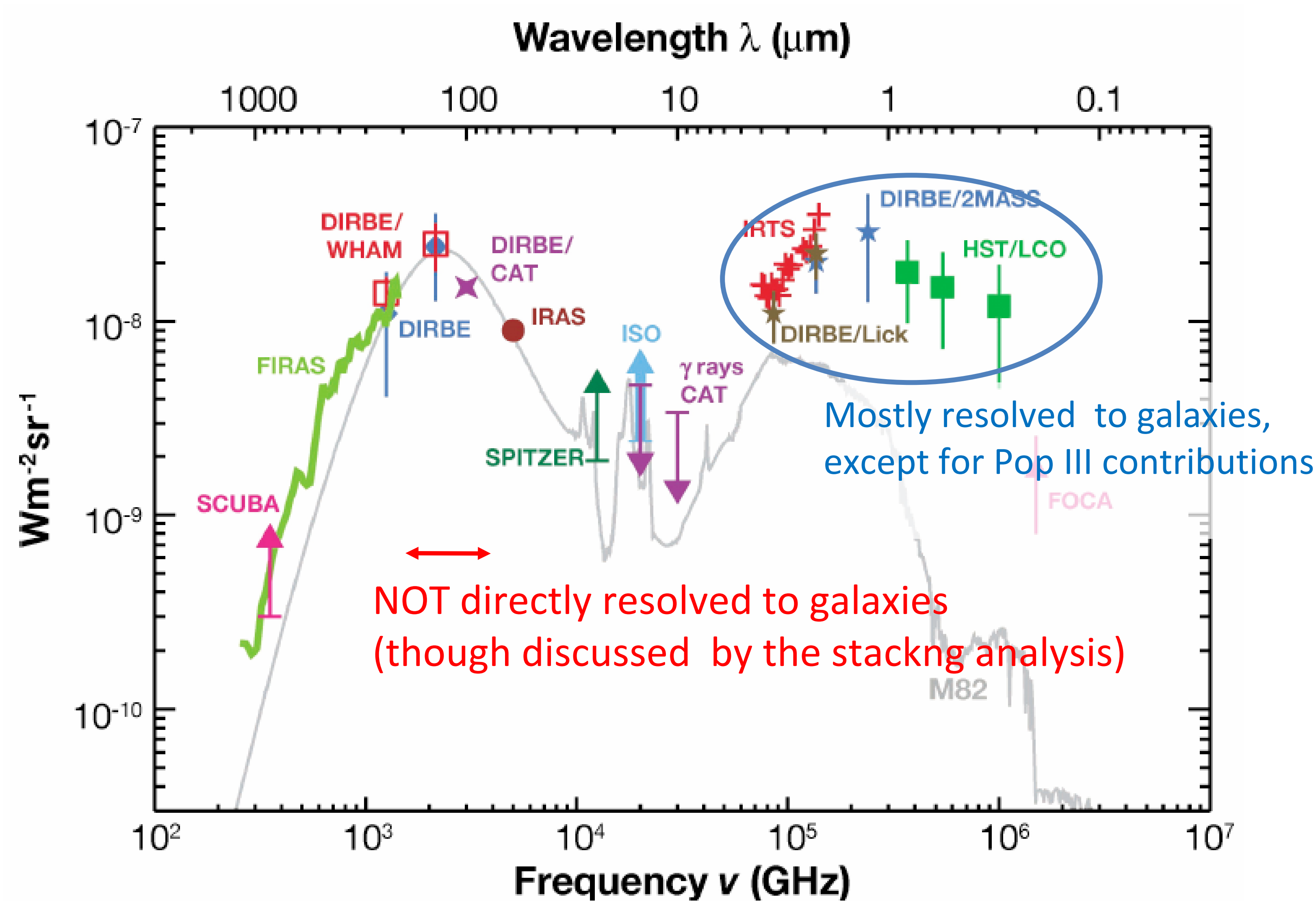


- Extreme sensitivity @0.6-5μm
  - Re-ionization sources @ z>7 may be identified and studied
- Suprime spatial resolution (68mas@2μm)
  - Origin of galaxies' morphology may be answered

etc. etc.

But even in 2017, mid-far IR wavelengths (20-400μm) has not yet been explored very much. THIS Wavelength range is ESSENTIALLY IMPORTANT, however, because ..

Cosmic Infrared Background :
the energy production history of the universe, a half of which is hidden by dust



SPICA will explore ..

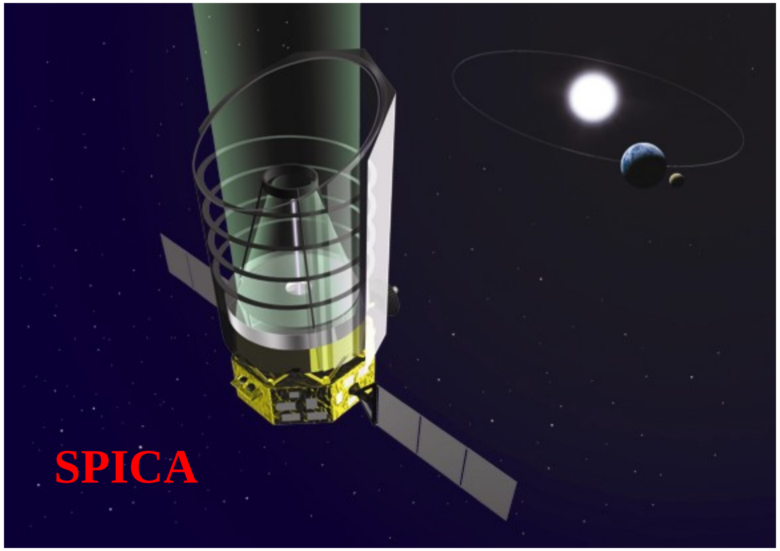
- #1: Nature of re-ionization sources
  - High-z atomic H line emitters : 斉藤(松原）
  - High-z molecular H2 line: 松原
  - Challenge detecting z>4 dust-obscured IR luminous population : 江上
- #2: Origin of CIRB
  - Resolving CIRB and its fluctuations: 白旗
- #3: Diagnostics of distant(up to z~3) IR galaxies
  - Atomic line spectroscopic diagnostics : 松原（長尾）
- #4: SMBH growth history
  - Search & Understanding obscured AGN out to z~6 : 秋山
- #5: Cosmic SF & mass assembly history
  - Distant clusters & enviromental effect on galaxy evolution : 小山

Description of Scientific Targets in “Extragalactic Science Section of MRD

Major Objective [1]

銀河の誕生と進化過程の解明

Resolution of Birth and Evolution of Galaxies

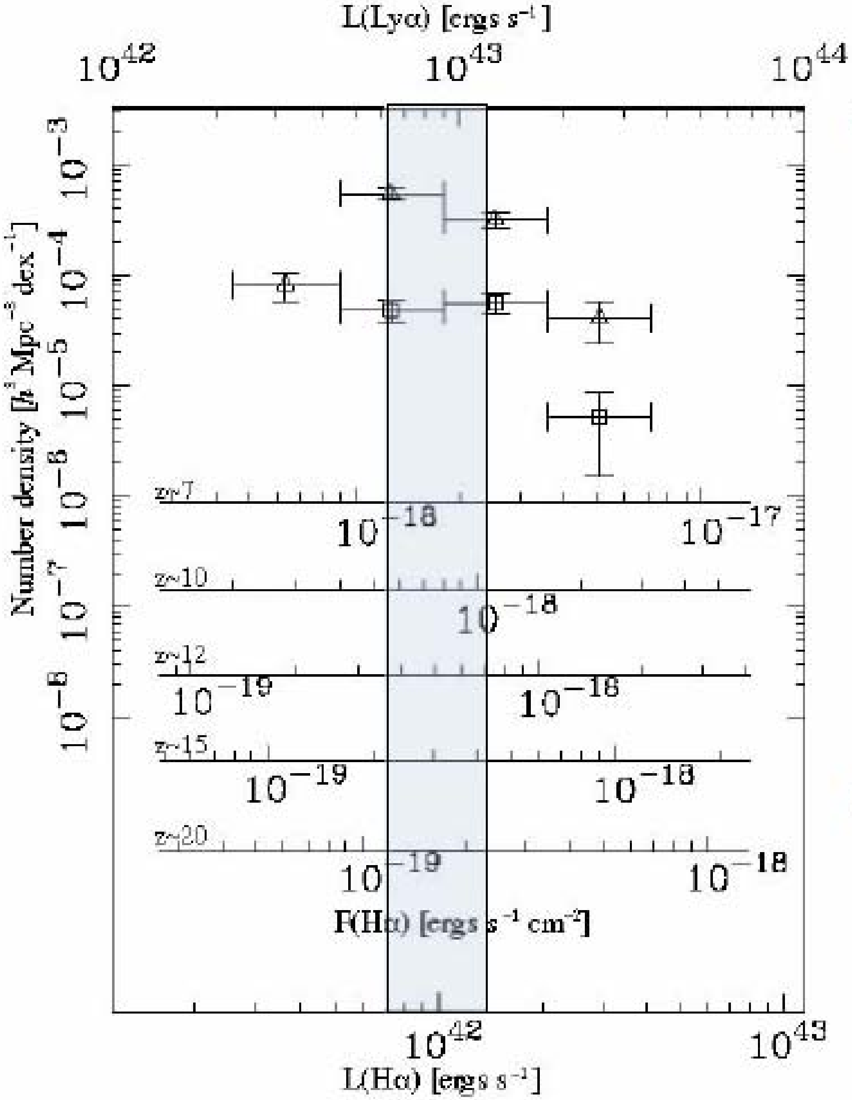


Nature of re-ionization sources

- 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@z~7-20 の検出



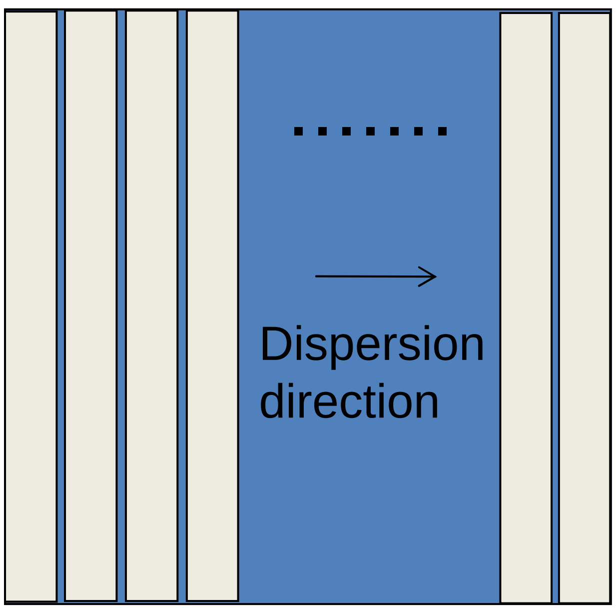
- z>7 における銀河の光度関数を「正しく」求める。
  - 本当に銀河は減少？
  - LAE とあわせ、IGM opacity から再電離に制限をつける。
- Cooling clouds (i.e., blobs) も検出可能？

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)

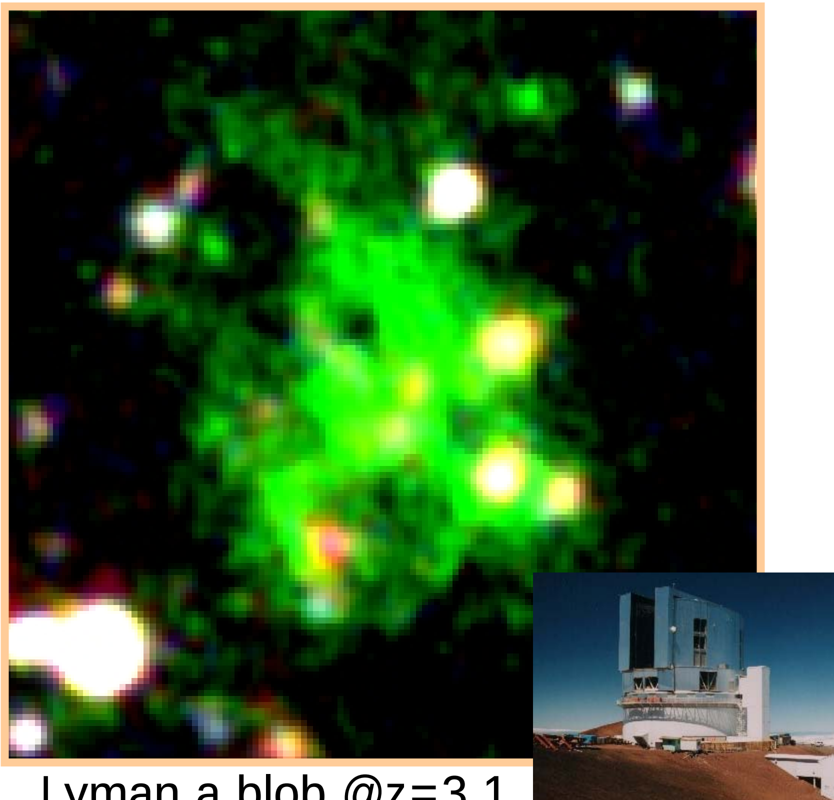
Emitter Search for z>7?

Star-formation Rate? Dust Extinction (with Hβ)?



MIRACLE's FoV 6'x6'

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



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

Legacy Science「種族III天体探査」(2)

** 概要 **宇宙再電離を担う「種族III天体」の候補である遠方 (赤方偏移7以上) の星形成銀河からの電離輝線を、放射エネルギーが赤方偏移下赤外線領域の分光観測で検出する。併せて銀河数密度 (光度関数) の進化から宇宙の再電離史に制限をつける。
具体的なターゲット: 主としてH-alpha。他、水素・ヘリウムの再結合線

番号	項目	HST	すばる等 地上8－10m	あかり Spitzer	Herschel Planck	ALMA	JWST	ELT	その他
A	同一の観測 （目的・手法・性能（波長・空間分解能・感度など）が全く同じ）								
B	同種の観測 （手法・性能は異なるが目的は全く同じ）	x	x	△	x	x	△	x	
C	視野			同様			4倍		
D	空間分解能			4倍			0.25倍		
E	感度			16倍			0.25倍		
F	波長分解能 or フィルターバンド数			同様			同様		
G	コントラスト比 （コロナグラフ）								

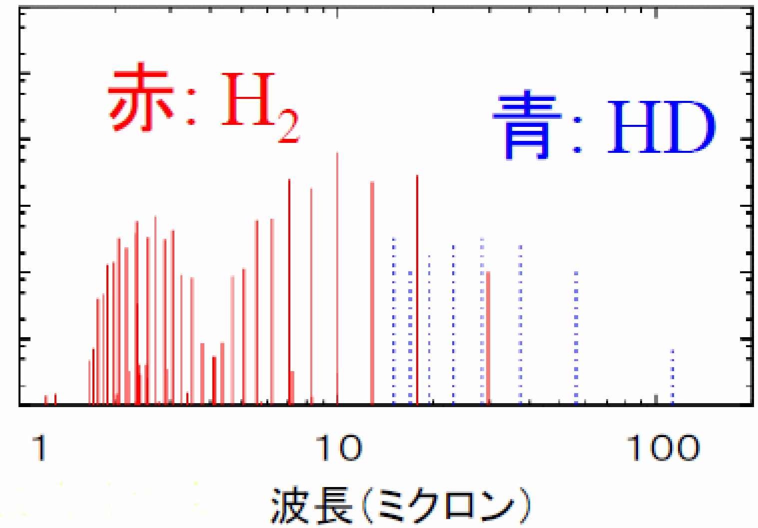
Legacy Science「種族III天体探査」(3)SWOT分析

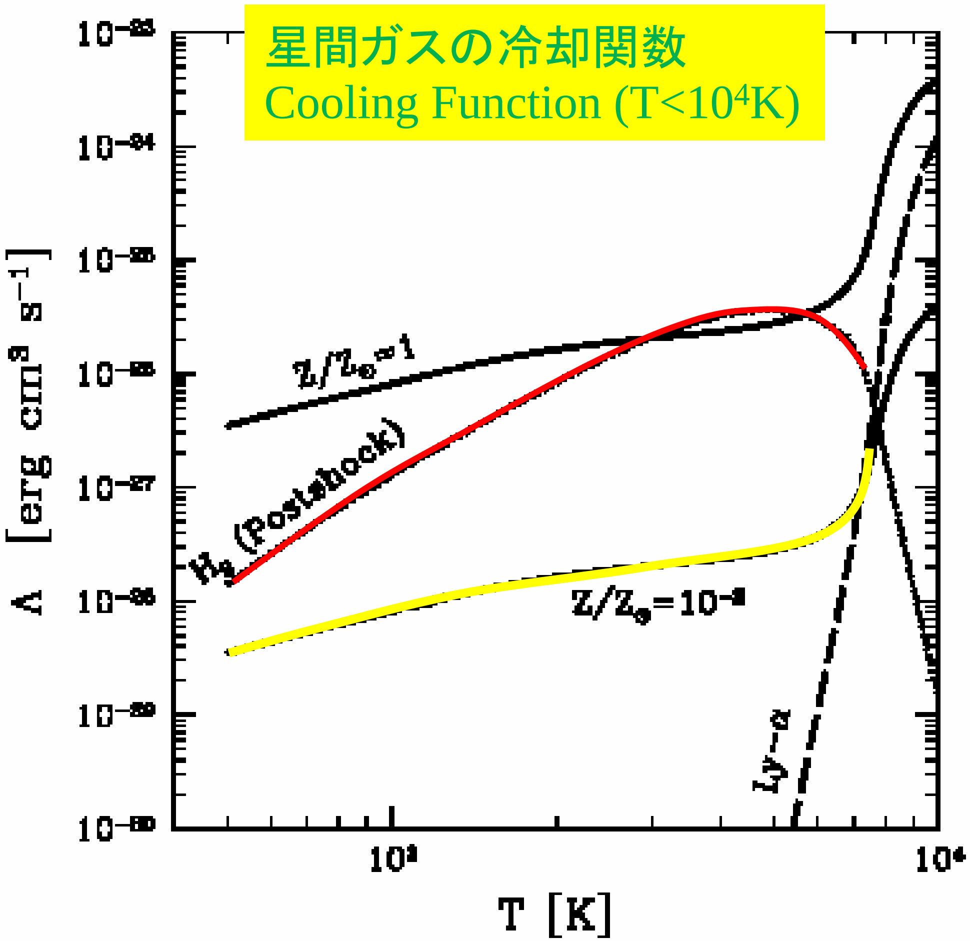
	良いこと	悪いこと
内的	**Strength**（強み） 等価幅の大きな輝線天体を効率よく探査できる	**Weakness**（弱み） Slit-scan 故、視野がやや限られる
外的	**Oppotunities**（機会） ALMA と連携すれば dust-obscured な星形成活動もトレースできる	**Threats**（脅威） JWST が5年先行

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

Mizusawa, Nishi and Omukai(2004)





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 ($T>10^4$K)
- H_2 rotation lines 回転線($T<10^4$K)

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

H_2 emission from Pop III: detection with SPICA is very challenging

- z~8での形成途上銀河からの(Omukai & Kitayama 2003) 0-0 S(1) 17μm フラックスは:
  - ~10^{-22}W/m^2 @M~$10^{11}M_{sun}$ 原始銀河
  - z~3でなら ~10^{-21}W/m^2
  - *BLISS で100時間積分してやっと届く・・*
- Z=3-4にも、非常に低金属度のライマンα輝線銀河やライマンブレーク銀河が存在する (Jimenez & Heiman 2006, nature, 4580)から、検出できる可能性がある
  - ただしターゲットをしぼりこんでおく必要

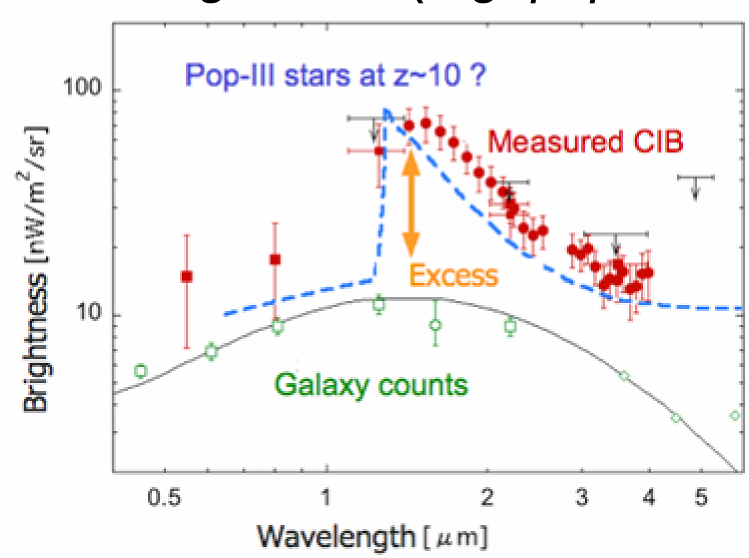
Origin of Cosmic IR Background

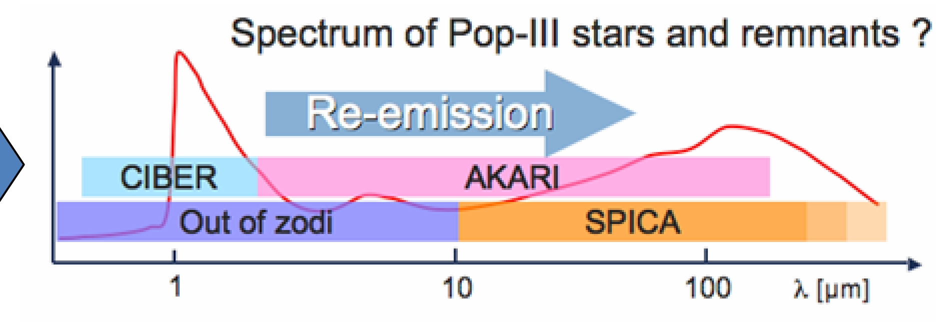
- 科学目的 Objective
  - 宇宙遠赤外線背景放射の大部分を個別天体に分解するとともに、遠赤外線背景放射の空間揺らぎの起源を明らかにする。
  - We will resolve the cosmic far-infrared background light into individual objects, and reveal the origin of the cosmic far-infrared background fluctuations.
- 科学目標 Target
  - 宇宙遠赤外線背景放射を、「あかり」の3倍以上の空間分解能により**個別の遠赤外線天体に分解**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**

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

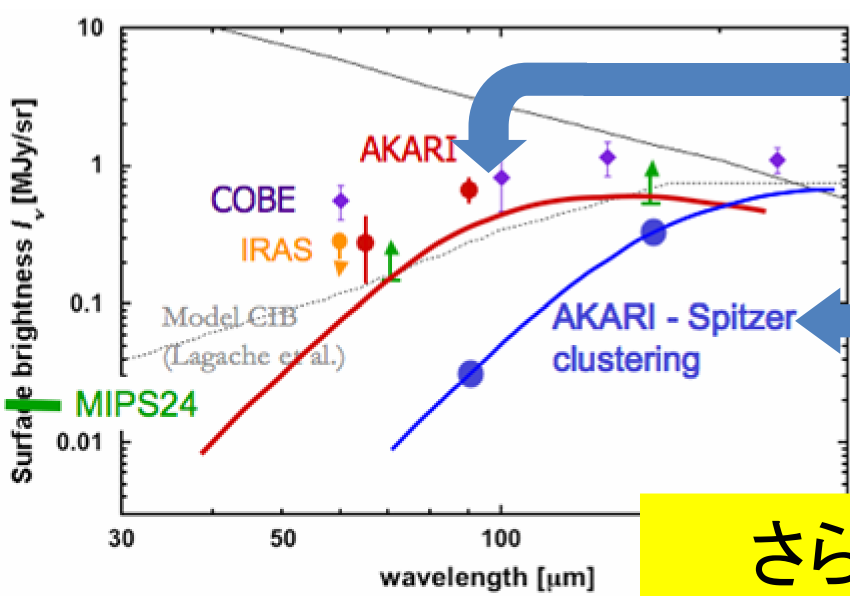
- *Proto-galaxies (e.g. pop-III stars, mini-quasars) at z~10?*





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)

さらに詳しくは白旗さんが話します

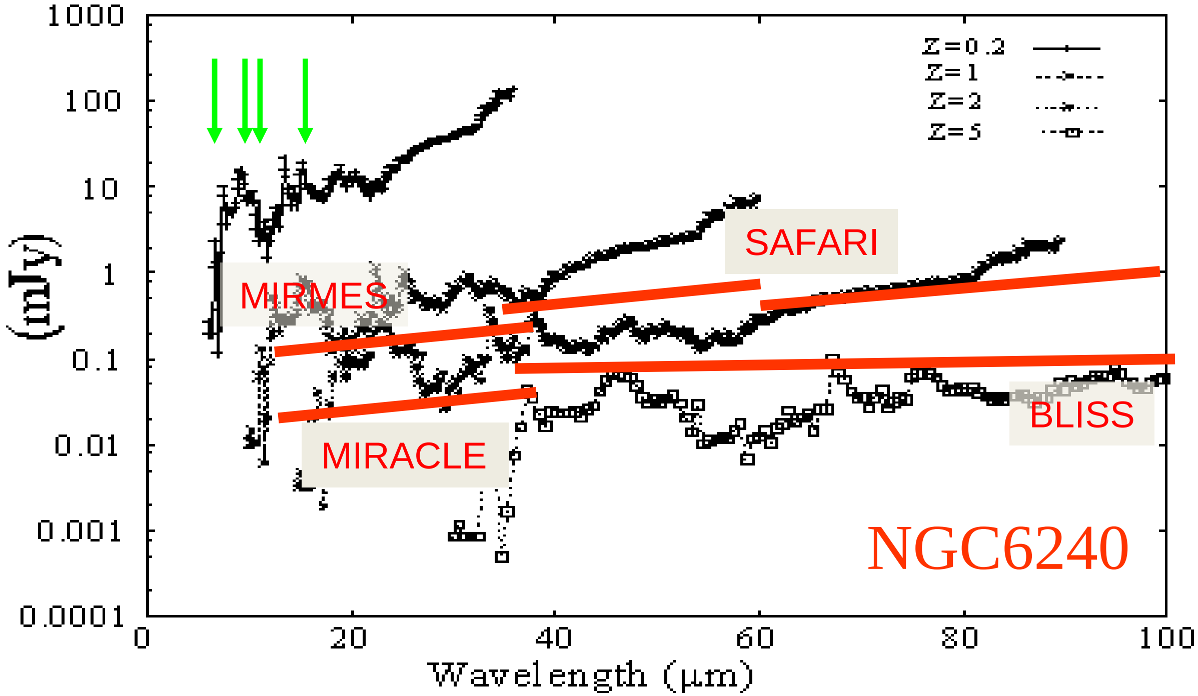
Diagnostics of distant IR galaxies

- 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!

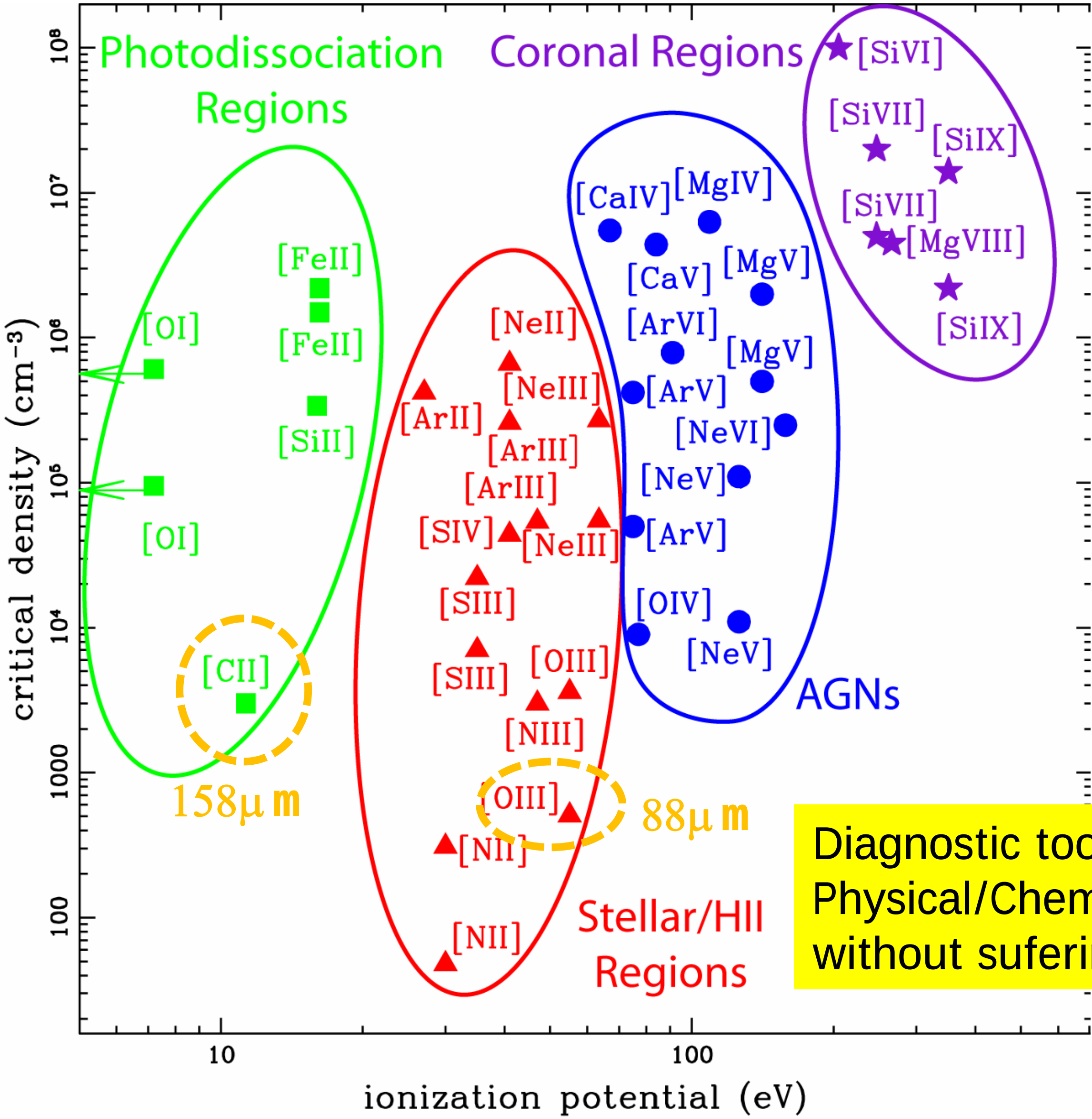
UIR band features at 3.3, 6.2, 7.6-7.8, 8.6, 11.2, 12.7μm

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, $n^{c}_{e}=5.4\cdot10^{5}$)

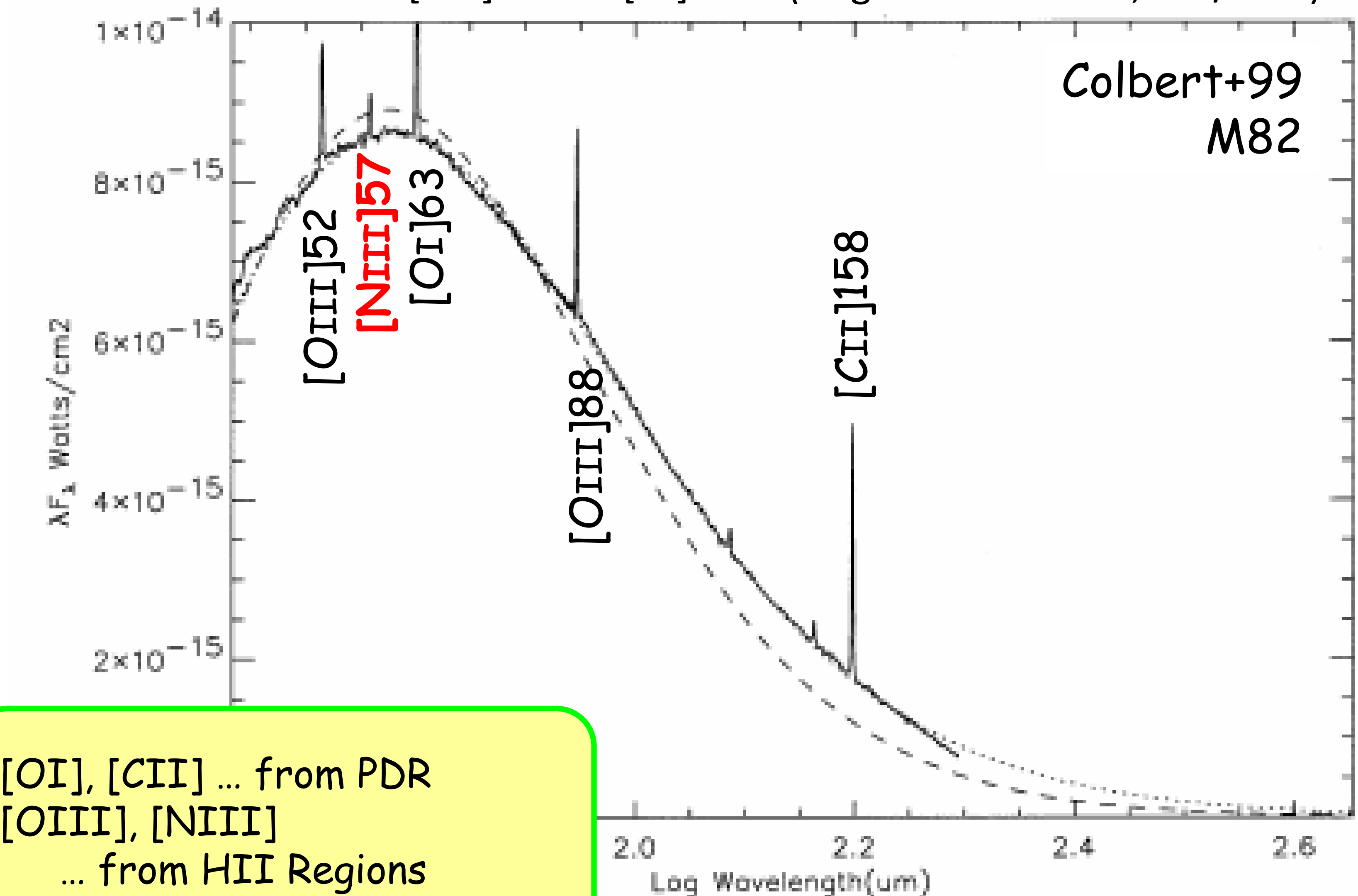
Numerous Atomic/Ionic Fine-structure Lines exist in the Mid- to Far-infrared



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

$\lambda/\Delta\lambda$ =1000 is necessary for the line diagnostics

Line/Continuum ratio : ~3 for [OI] 63; ~2 for [CII] 158 & [OIII] 88 ;
but ~0.3 for [N II] 122 & [OI] 145 (Negishi et al. 2001, ISO/LWS)



[OI], [CII] … from PDR
[OIII], [NIII]
… from HII Regions

Courtesy to Toru Yamada-san, Shinki Oyabu-san

Mid-IR Metallicity Diagnostics

(1) Σ [X^{i+}/H^{+}]

[NeII]12.8 + [NeIII]15.6 Ne/H
[ArII]6.98 + [ArIII]8.99 Ar/H
[SIII]18.7 + [SIV]10.5 S /H
[NII]122 + [NIII]57.2 N /H

(e.g., Verma+03; Panuzzo+03)

Requires H^{+} info…
(Br alpha @4micron etc…)

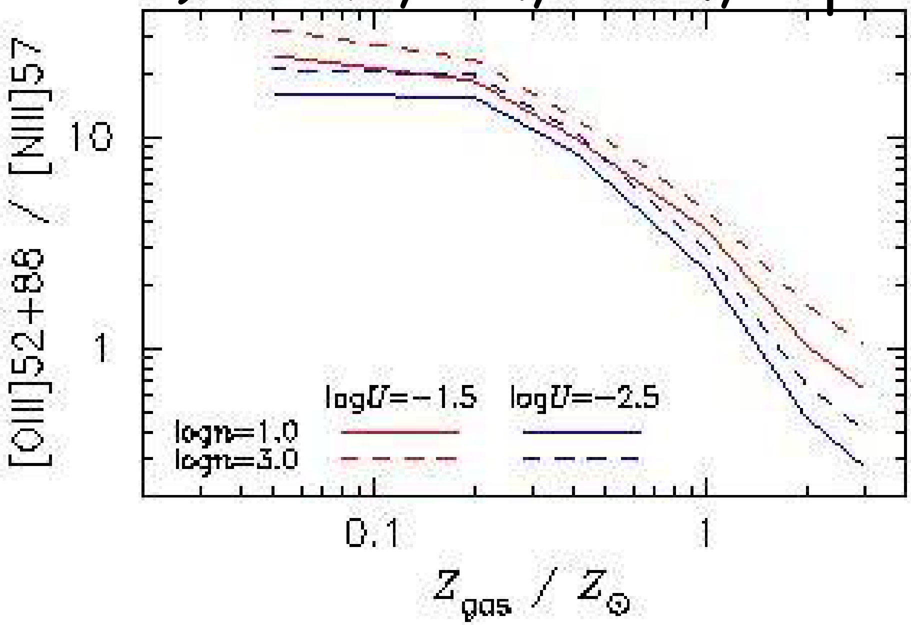
TN, RM, et al., in prep.

(2) N/O∝O/H

For dusty galaxies
(ULIRG, SMG, normal SBG)

ISO/LWS: only z~0
Herschel/PACS: z<0.2

1<z<2 seems very interesting!!



Courtesy to Tohru Nagao-san

Success Cliterion & Observation Plan

- 成功基準:
  - 赤方偏移2～3までの様々な銀河について、広帯域中分散分光観測の統計的研究を行うことにより、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。
- 観測計画:
  - SAFARI及びMIRMESによる10～210μm中分散(R～1000)分光観測を、様々な赤方偏移の塵に覆われた赤外銀河(合計200個)について実行
    - 200個×(SAFARI 1hr + MIRMES 1hr)＝net 400hrs
  - MIRACLEによる周辺領域も含む撮像
  - BLISSによる比較的遠方天体の~400μmまでの精密・超高感度分光

Super-Massive Black-Hole growth history

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。

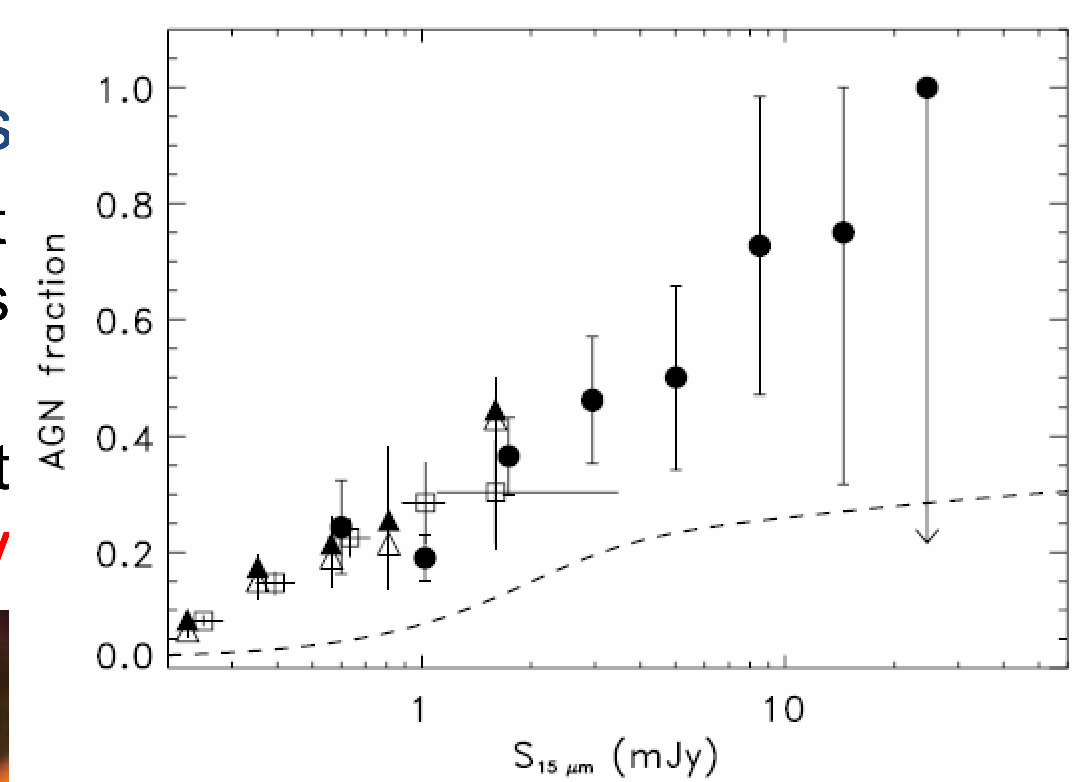
    ※太陽の数億個に相当する質量があると思われるブラックホール
  - In order to understand the role of supper-massive black holes (SMBHs) in the galaxy evolution, we will make a survey for the forming SMBHs, that may not be observed easily in other methods due to the obscuration by dust, from the present to the early universe.
- 科学目標　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

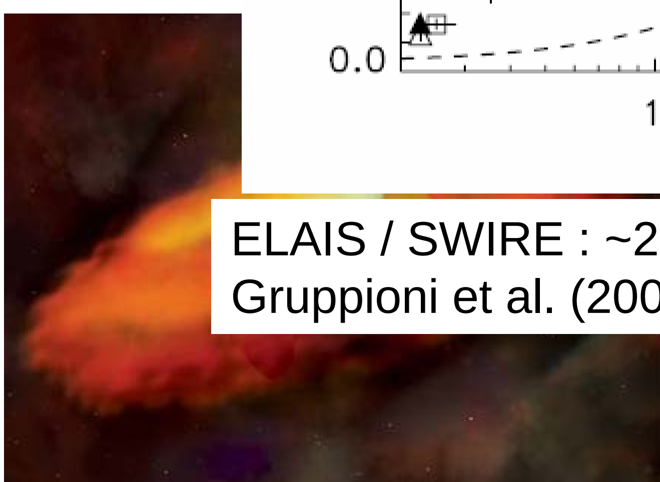
中間赤外線中分散分光装置 MIRMES　**遠赤外線撮像分光装置 SAFARI**

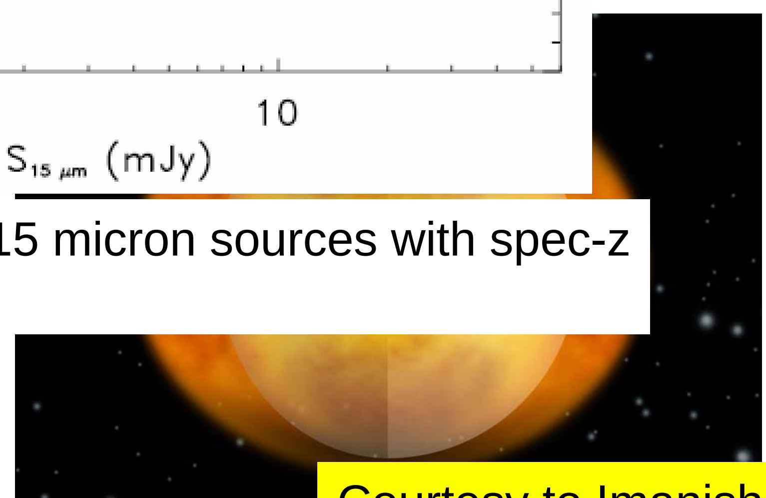
Universe obscured by dust

- Key iss xies :
  - Relat per Mass
  - AGN al spect ed in dusty



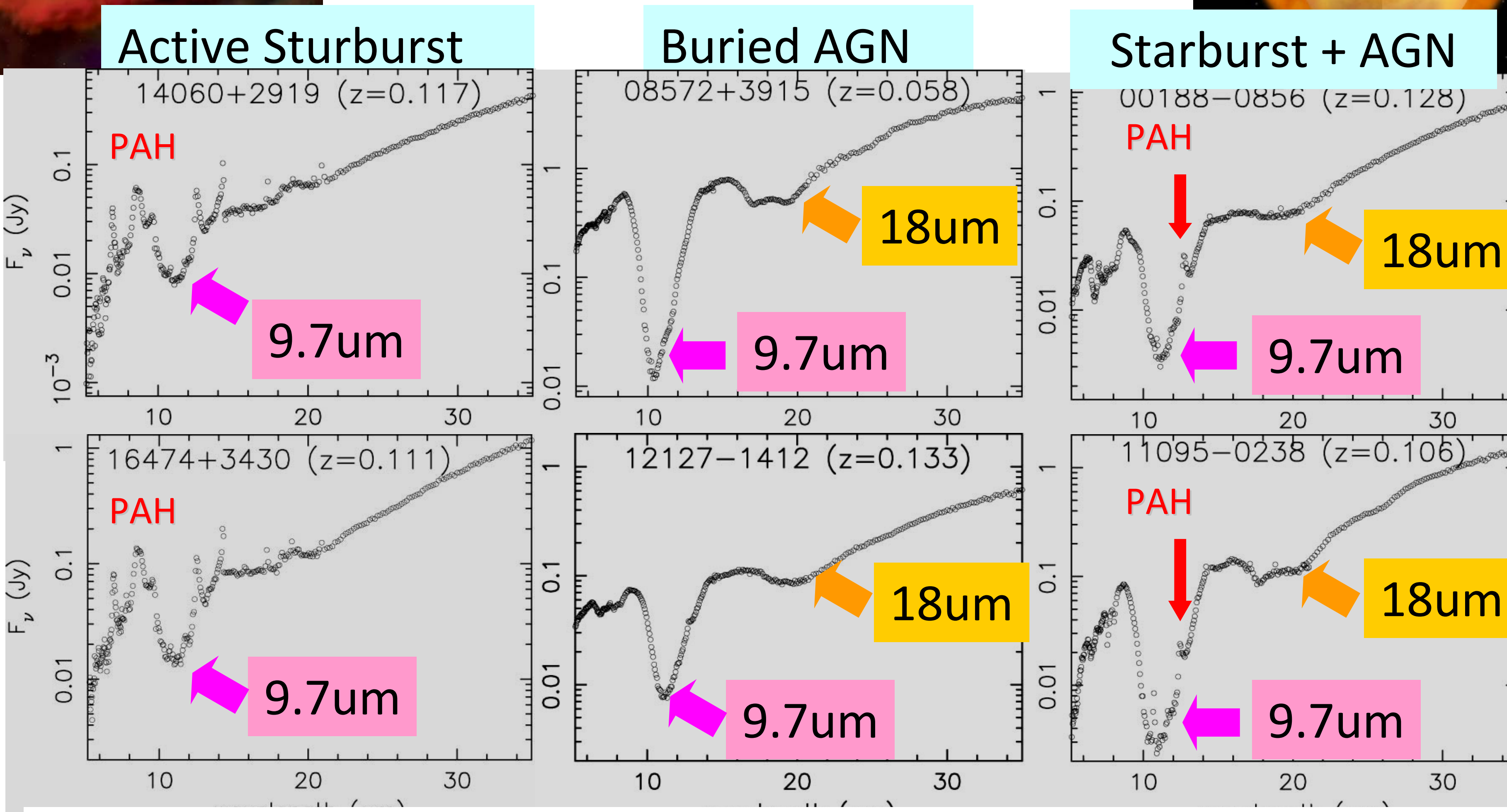
ELAIS / SWIRE : ~200 15 micron sources with spec-z
Gruppioni et al. (2008)





Courtesy to Imanishi-san

5-35 μm spectra of ULIRGs



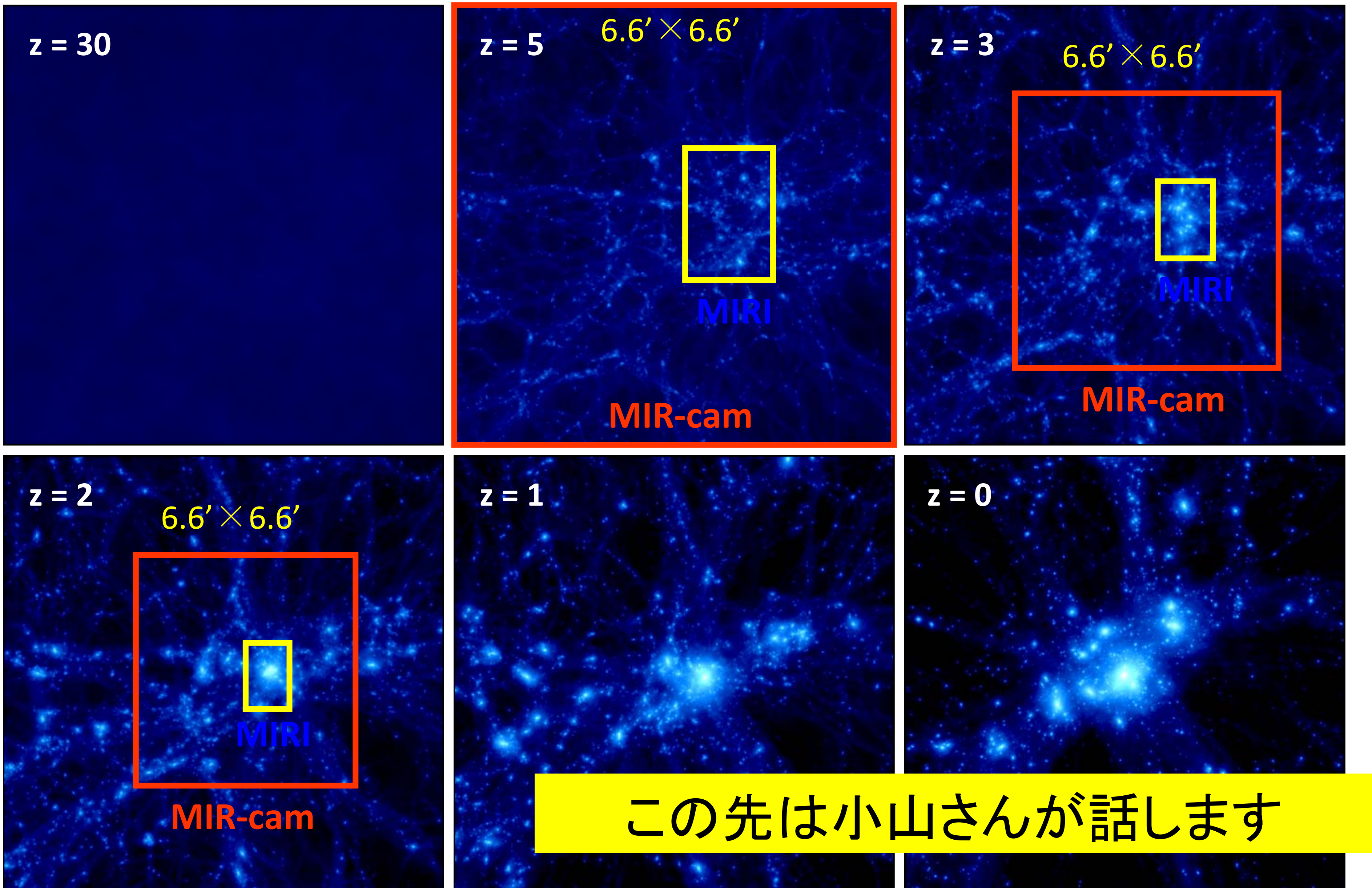
With Spitzer & AKARI, only 24 micron-very-bright ULIRGs (biased sample) could be studied at z > 1: SPICA enables us to go to z > 3 and to general ULIRGs at z > 1 !!

この先は秋山さんが話します

Cosmic SF & Mass Assembly History

- 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.

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)

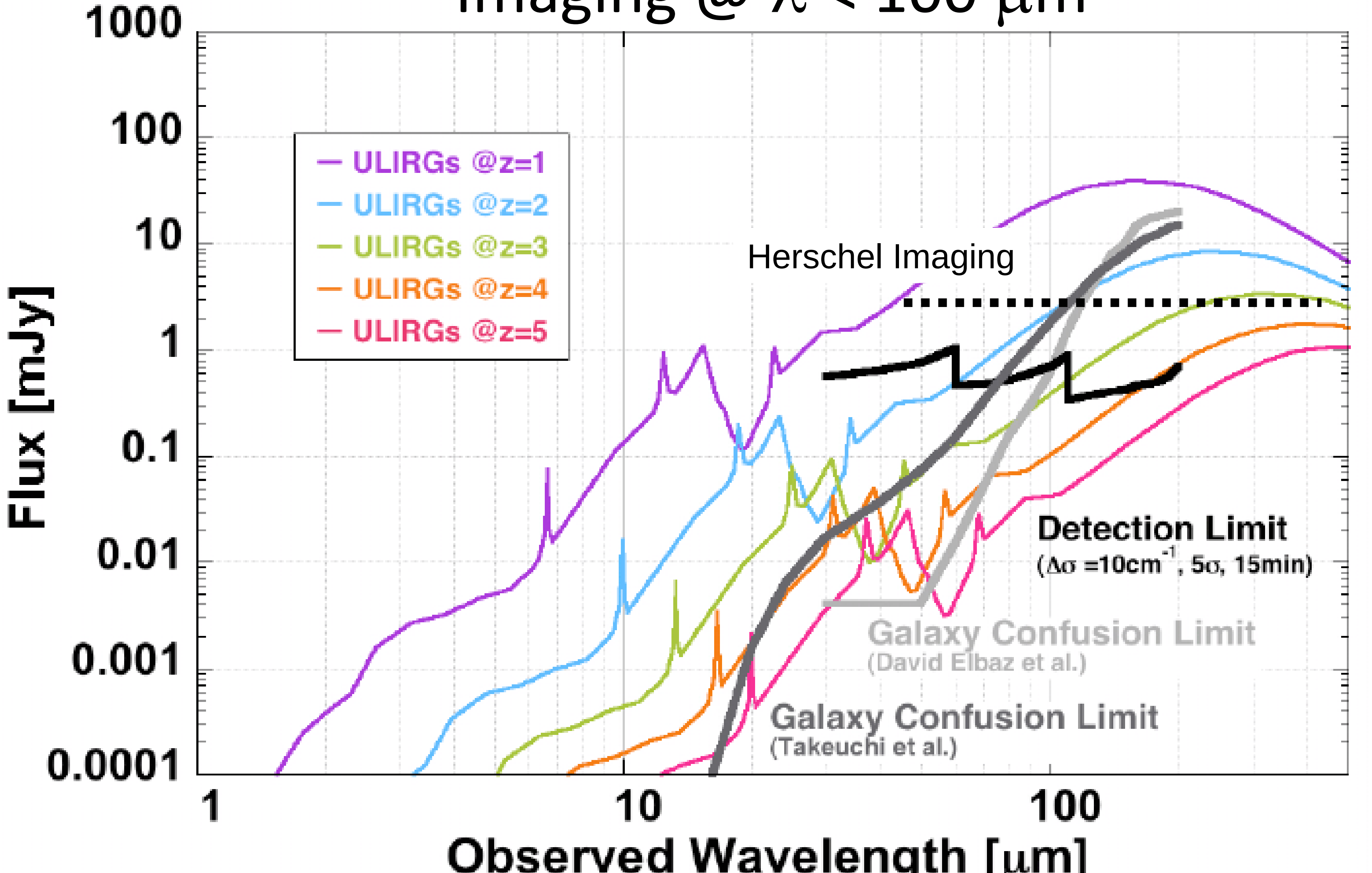
Yahagi et al. (2005)

ここでいったん中断です

Role of SPICA for future study of distant Universe

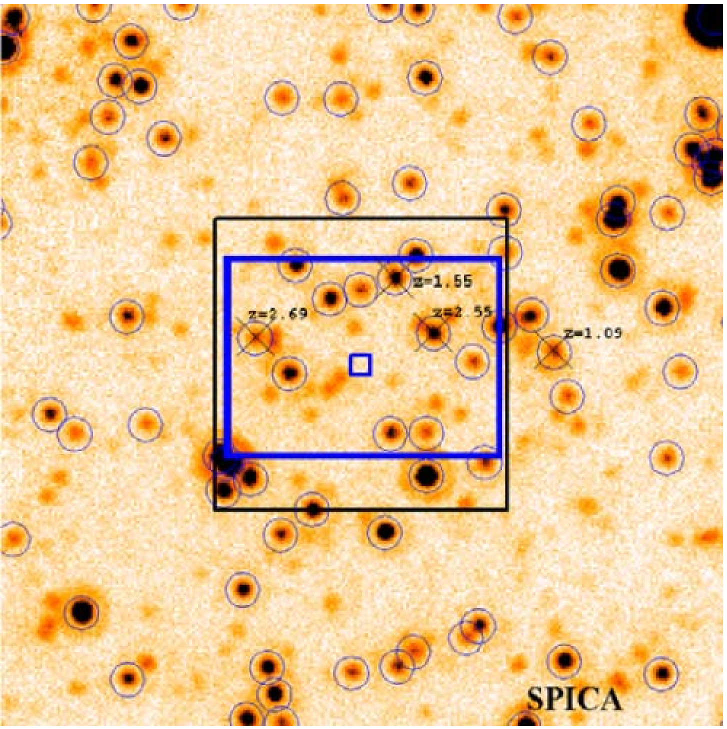
- Overwhelming Imaging Sensitivity at 20-100 μm (MIRACLE, SAFARI)
  - *Overwhelming mapping speed !!*
  - MIRACLE should have large FoV as much as possible
- Capability of spectro-imaging at 35-210μm (SAFARI)

Overwhelming Sensitivity
Imaging @ λ < 100 μm

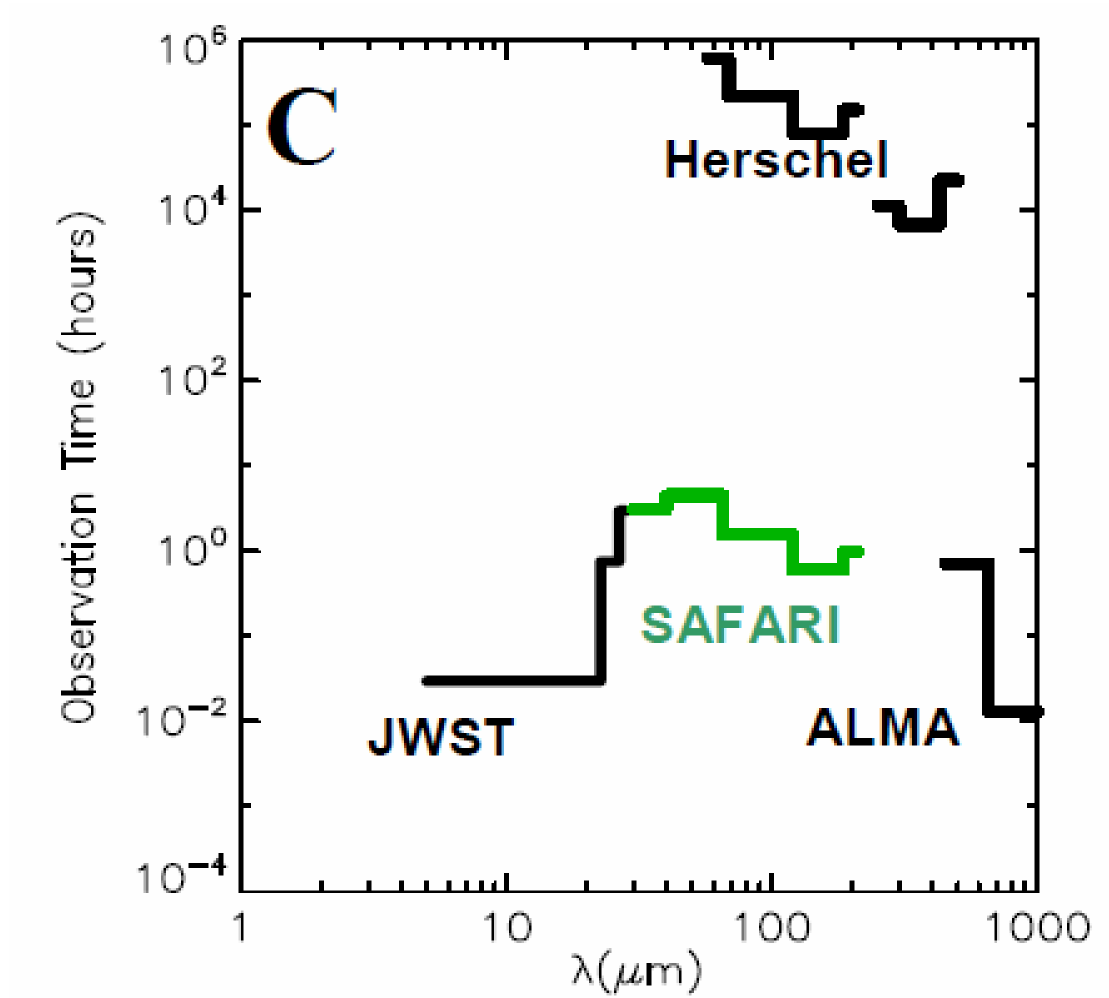


SAFARI's advantage on Mapping Speed

- Multiplex advantage can only appear in the low-resolution, "SED" mode($\lambda/\Delta\lambda$~100).
- With $\lambda/\Delta\lambda$=100, the strong lines ([OI] & [CII]) can still be detected



GOODs-S MIPS S_{24}>=100μJy sources , corresponding 2-4mJy at 100μm (M82 SED at z=1-2)



Role of SPICA for future study of distant Universe

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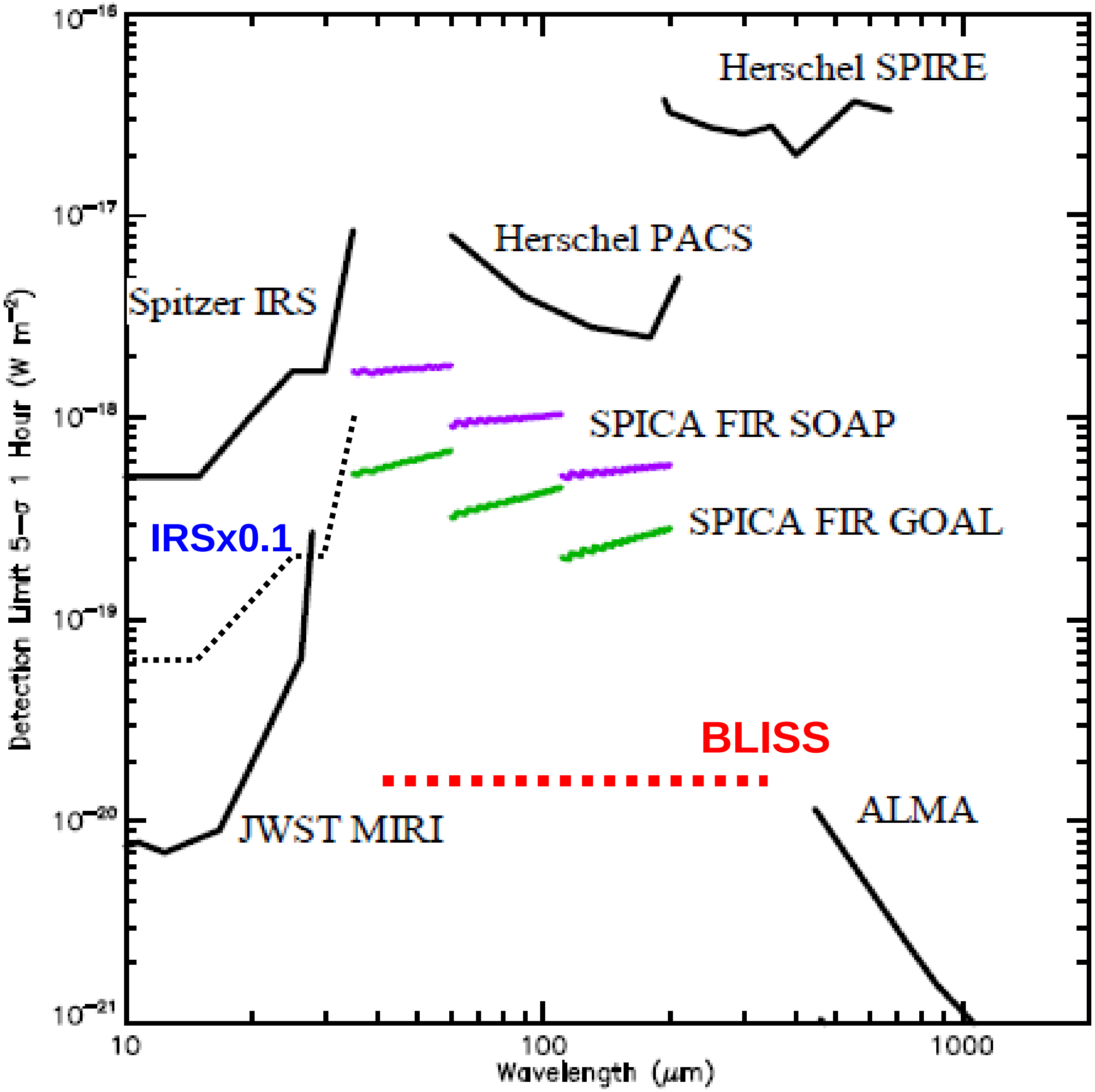
- Overwhelming Spectroscopic sensitivity at 30 – 400 μm (MIRMES, SAFARI, BLISS)

Sensitivity for spectral lines
(1 hour, 5σ)



今後の課題･問題点

- Nature of re-ionization sources
  - 目標が高すぎないか。Feasibilityをよく検討し、成功基準の見直しを。
  - JWSTが成果を出した後、それをどう活かす？
  - 他のアプローチは？（重力レンズ? GRB afterglow?)
- Super-Massive Black-Hole growth history
  - 既知天体に重きを置くのか、新発見天体に重きをおくのか？
- Cosmic SF & Mass Assembly History
  - JWSTでも柱となるサイエンス。どのような天体〔銀河団？〕をどれくらいの広さでカバーすることが本質的か、さらにつめる
- どの科学目標についても、観測計画の具体的検討、必要な観測時間の見積もりが急務

  → Legacy programとしての現実性

  → ミッション要求に反映 （そろそろ「要求」はFIXしなければならない！）

- 波長分解能は今のところ中分散で充分と考えているが？
  - 高分散分光で拓くKey Science Objectiveは？（例えば水素分子吸収線をQSOを背景に見れないか？）