「あかり」が切り開く
銀河系外アストロケミストリーの世界

下西　隆
(東北大学)

「あかり」サイエンスワークショップ@ NAOJ
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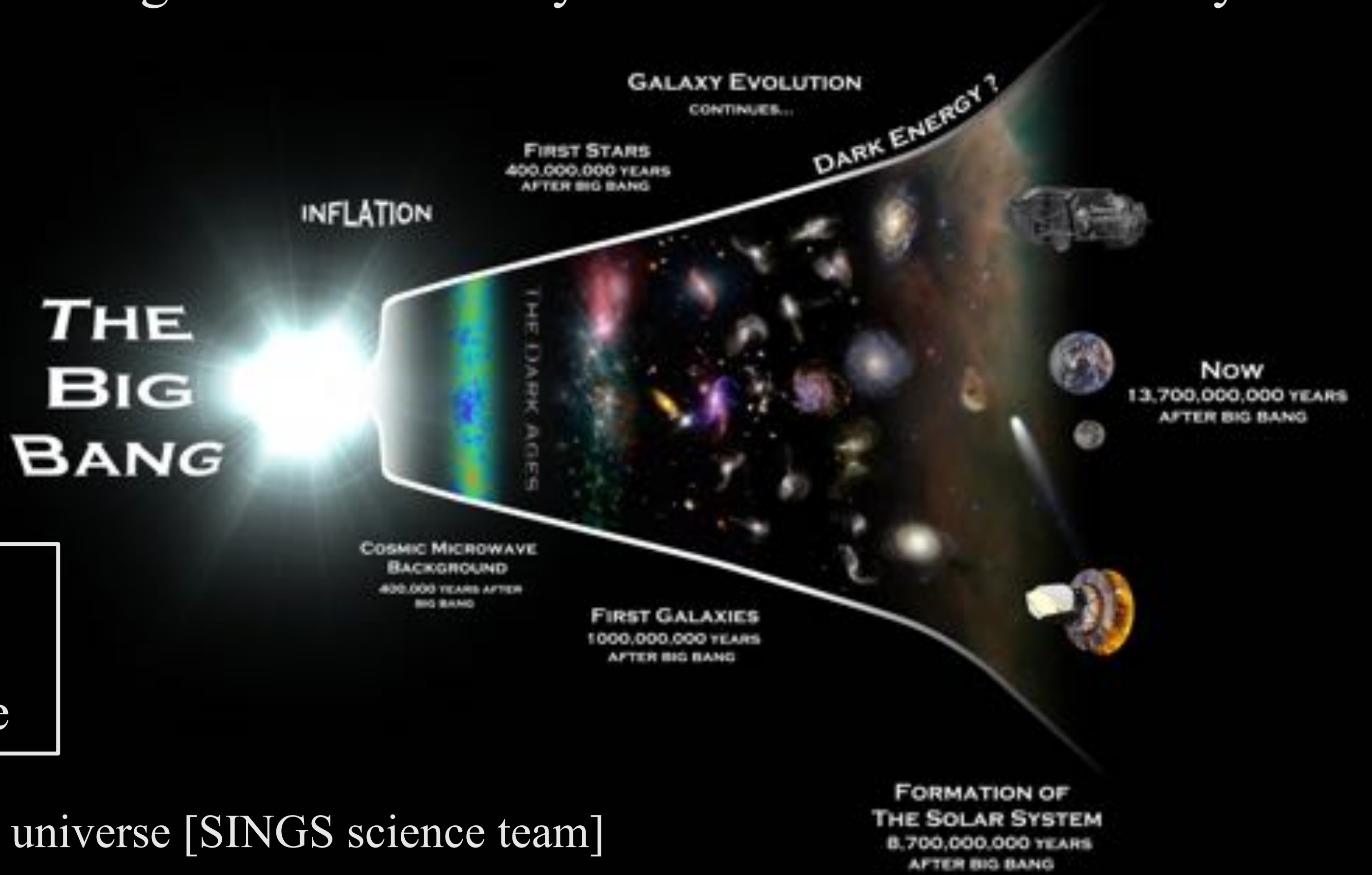
Extragalactic Astrochemistry

- How do environmental characteristics of galaxies affect chemical properties of interstellar medium?
- What is the effect of galactic metallicity on the interstellar chemistry?



Metal (astronomy): Heavy elements other than H and He

Fig.1 Evolution of the universe [SINGS science team]

The Large and Small Magellanic Clouds

- Nearest star-forming galaxies

 —$d_{LMC/SMC}$ = 50/60 kpc[1] (1” = 0.25/0.3 pc)

 —nearly face-on[2] (LMC, i ~35°)

- Low metallicity[3]

 —LMC : ~1/2-1/3, SMC : ~1/5-1/10 of solar neighborhood

 => This metallicity corresponds to that of the past universe at z = 1 – 2, which is close to an epoch of peak star-formation[4]

[1]Alves, 2004, [2]Westerlund, 1990, [3]Luck et al. 1998
[4] e.g., Hopkins & Beacom 2006, Rafelski et al. 2012

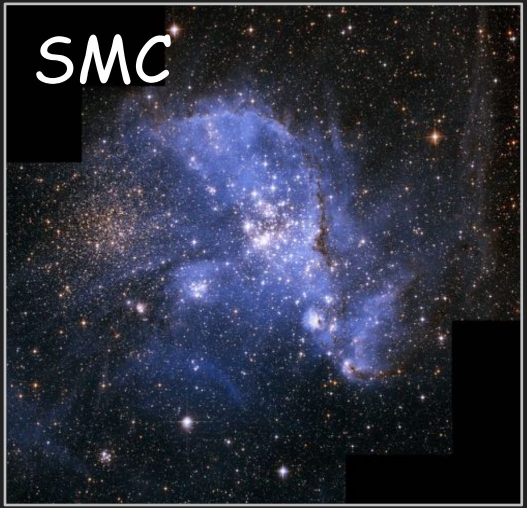


Fig.2 Optical images of the LMC and SMC
[Ref. E. Slawik (LMC), A. Nota/ESA, STScI (SMC)]

Environmental characteristics of LMC/SMC

- Elemental abundances

— low-metallicity and different C, N, O, S relative abundances

(e.g., Dufour+ 1982, Andrievsky+ 2001, Korn+ 2002, Rollenston+ 2002)

- Interstellar ultraviolet radiation field

— 10–100 times higher than typical Galactic value
(Israel & de Graauw, 1986, Tumlinson+ 2002, Browning+ 2003)

- Dust temperature

— higher than our Galaxy (e.g., MW: 15–19K, LMC: ~22–25K, SMC: ~30K, Aguirre+ 2003, Sakon+ 2006, results for diffuse clouds)

- Cosmic-ray density (cosmic-ray ionization rate)

— 3 to 4 times smaller than the solar neighborhood

(Abdo+ 2009, 2010 based on gamma-ray observations by FERMI

Infrared observations of ices

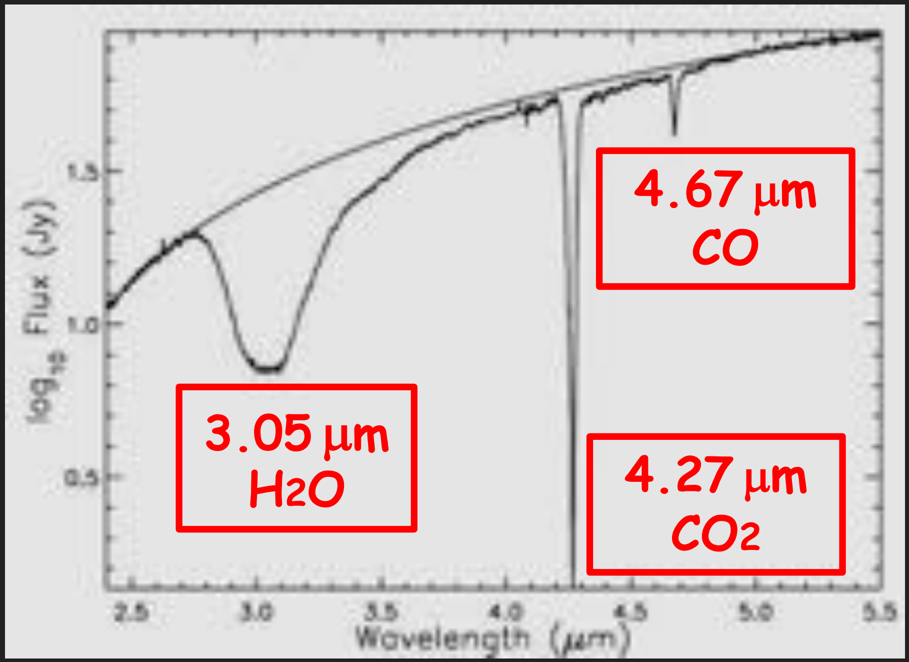


Fig.3 ISO-SWS spectrum of an embedded YSO AFGL989 [Gibb et al. 2004]

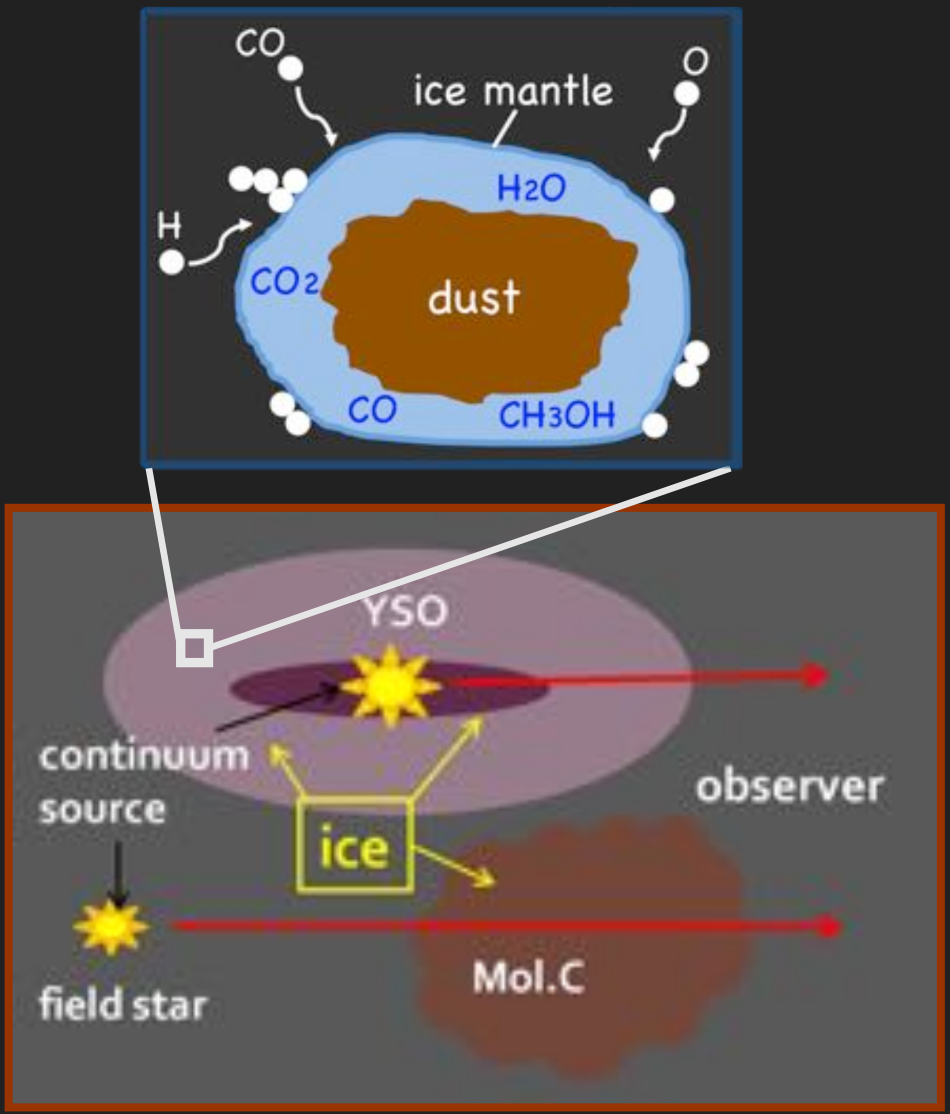


Fig.4 Ices in dense and cold molecular clouds

Ice observations for Galactic objects

- Infrared spectroscopic observations of ices toward various objects[1] (including high-/low-mass YSOs, quiescent clouds, extragalaxies)
- Detections of similar molecular species in comets[2]

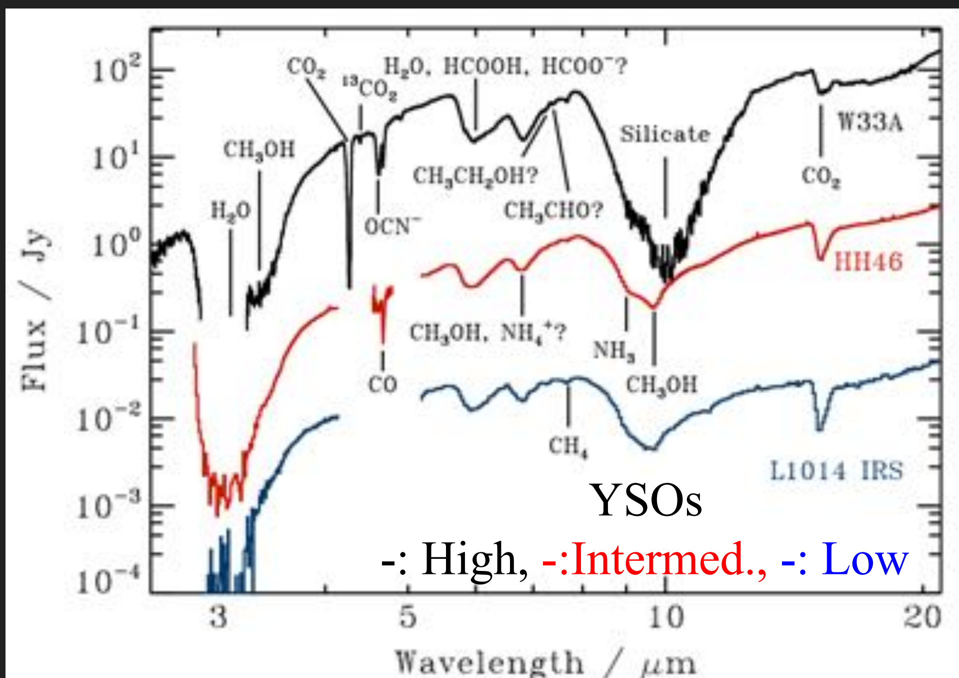


Fig.5 Infrared absorption spectrum of ices toward various targets [Oberg+ 2011]

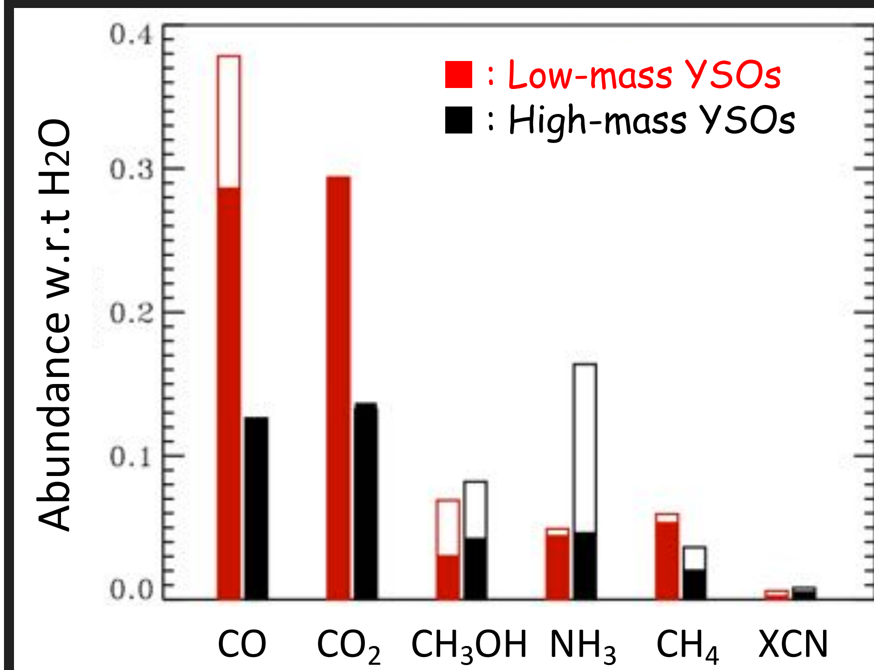
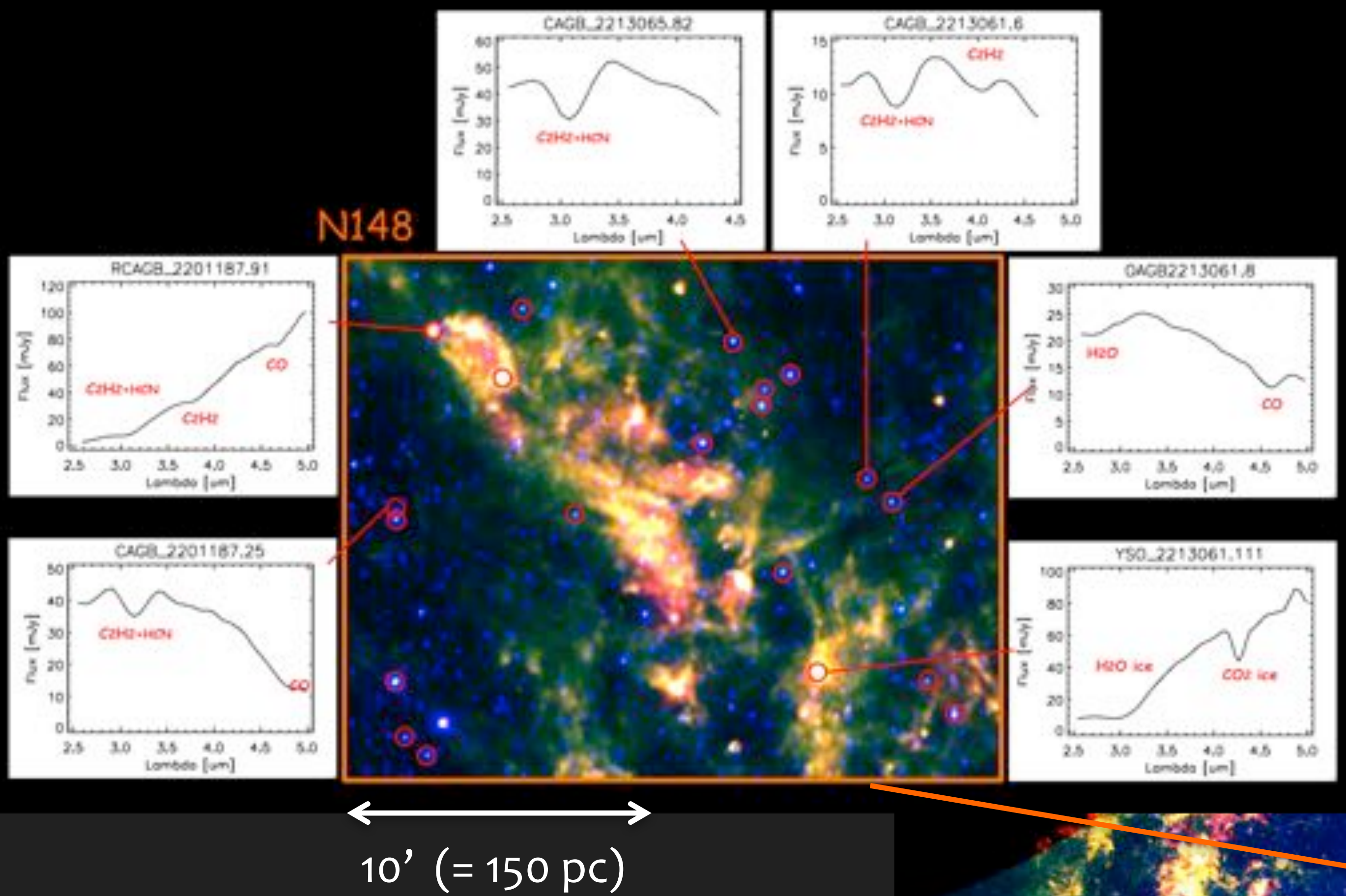


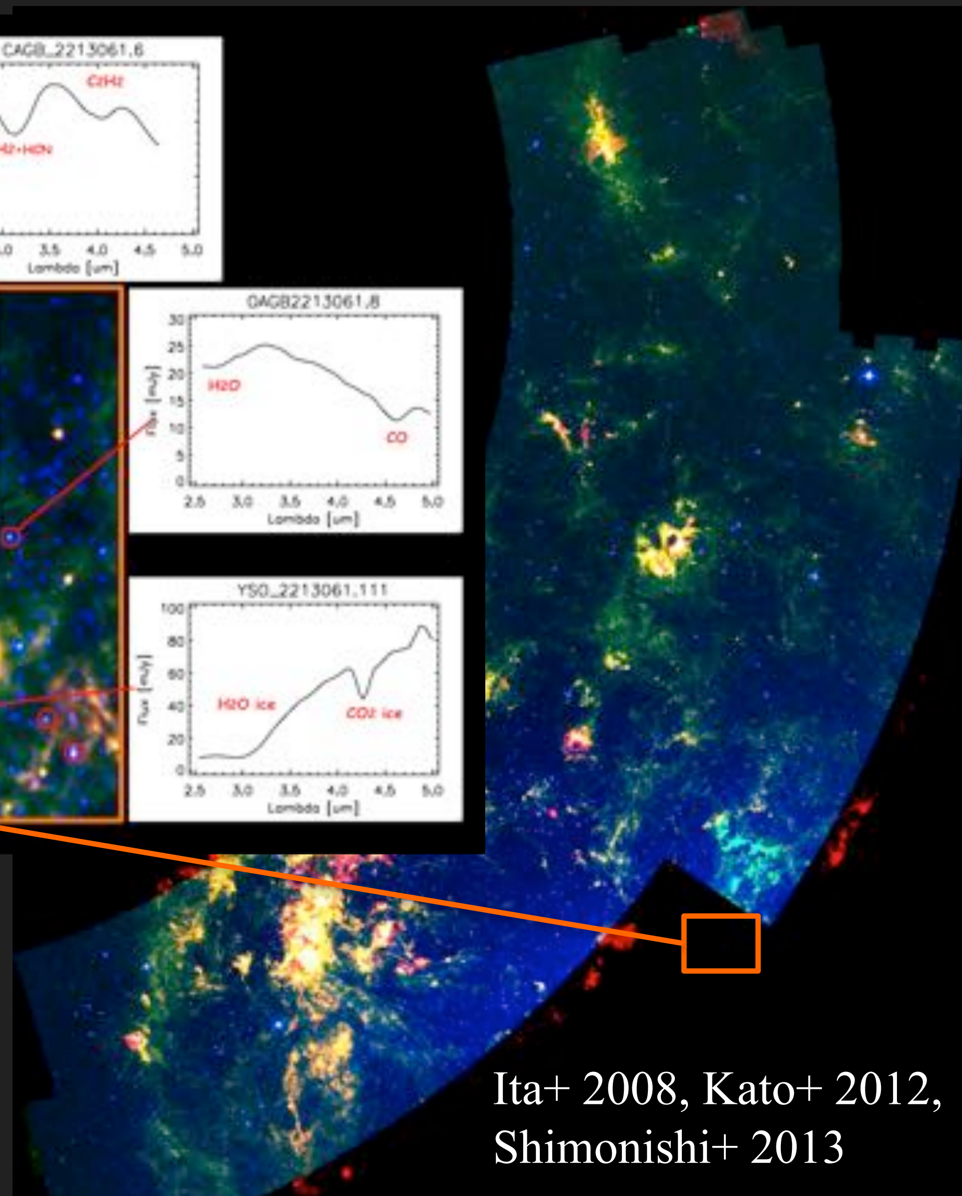
Fig.6 Typical abundances of ices around high-/low-mass YSOs [Oberg+ 2011]

[1] e.g., Boogert+ 2015, [2]Ehrenfreund+ 2000, 2002, Ootsubo+ 2012

AKARI/IRC survey of the LMC (LSLMC)



Complementary to the Spitzer SAGE-Spec survey [Kemper+ 2010; Woods+ 2011, also see Seale+ 2009, 2011].



Ita+ 2008, Kato+ 2012, Shimonishi+ 2013

Fig.7 *AKARI* three-color image of the LMC (Blue: 3 μm, Green: 7 μm, Red: 15 μm)

Ice observations for LMC/SMC YSOs

Fig.8 Infrared spectrum of a high-mass YSO in the LMC

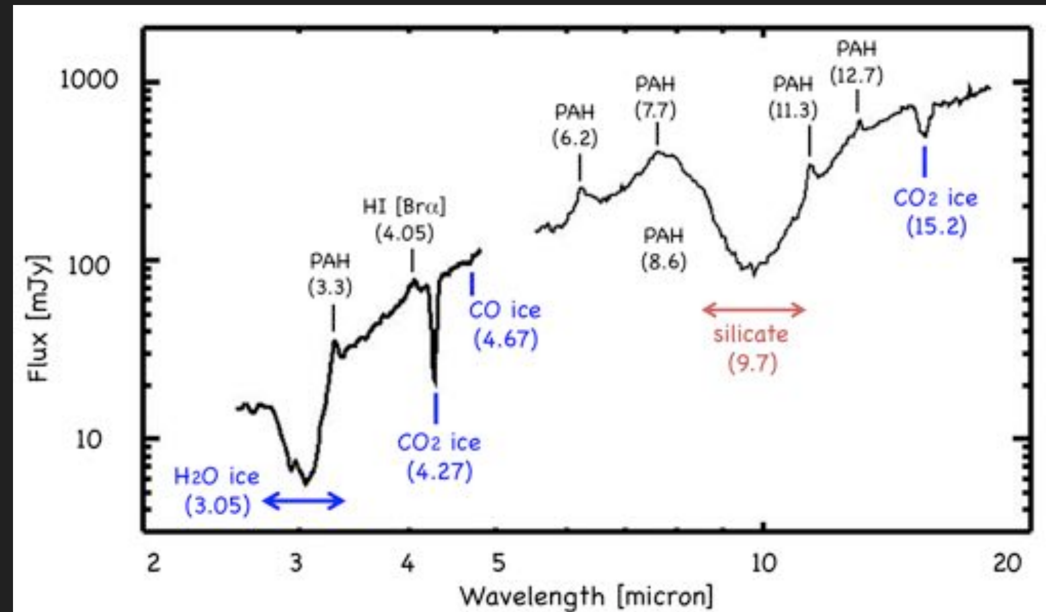


Table.1 Summary of ice detections toward high-mass YSOs in the Magellanic Clouds

λ [μm]	Cloud	No.	Ice band	References
2-5 (AKARI, VLT)	LMC	20	H_2O, CH_3OH, CO_2, CO, (XCN)	van Loon+ 2005; Oliveira+ 2006, 2011; Shimonishi+ 2008, 2010, 2012, 2016a
	SMC	12	H_2O, CO_2, CO	van Loon+ 2008; Oliveira+ 2011, 2013; Shimonishi+ 2012
5-20 (Spitzer)	LMC	54	(H_2O), CO_2, (NH_3)	van Loon+ 2005; Oliveira+ 2009, 2011; Seale+ 2009, 2011; Shimonishi+ 2016a
	SMC	15	(H_2O), CO_2	Oliveira+ 2011, 2013
60-70 (Spitzer)	LMC	5	H_2O	van Loon+ 2010a
	SMC	1	H_2O	van Loon+ 2010b

Chemical compositions of ices in the LMC (1/2-1/3 lower metallicity)

- Higher abundance in LMC
- Similar between LMC and MW
- Less abundant in LMC
- Few reliable estimate

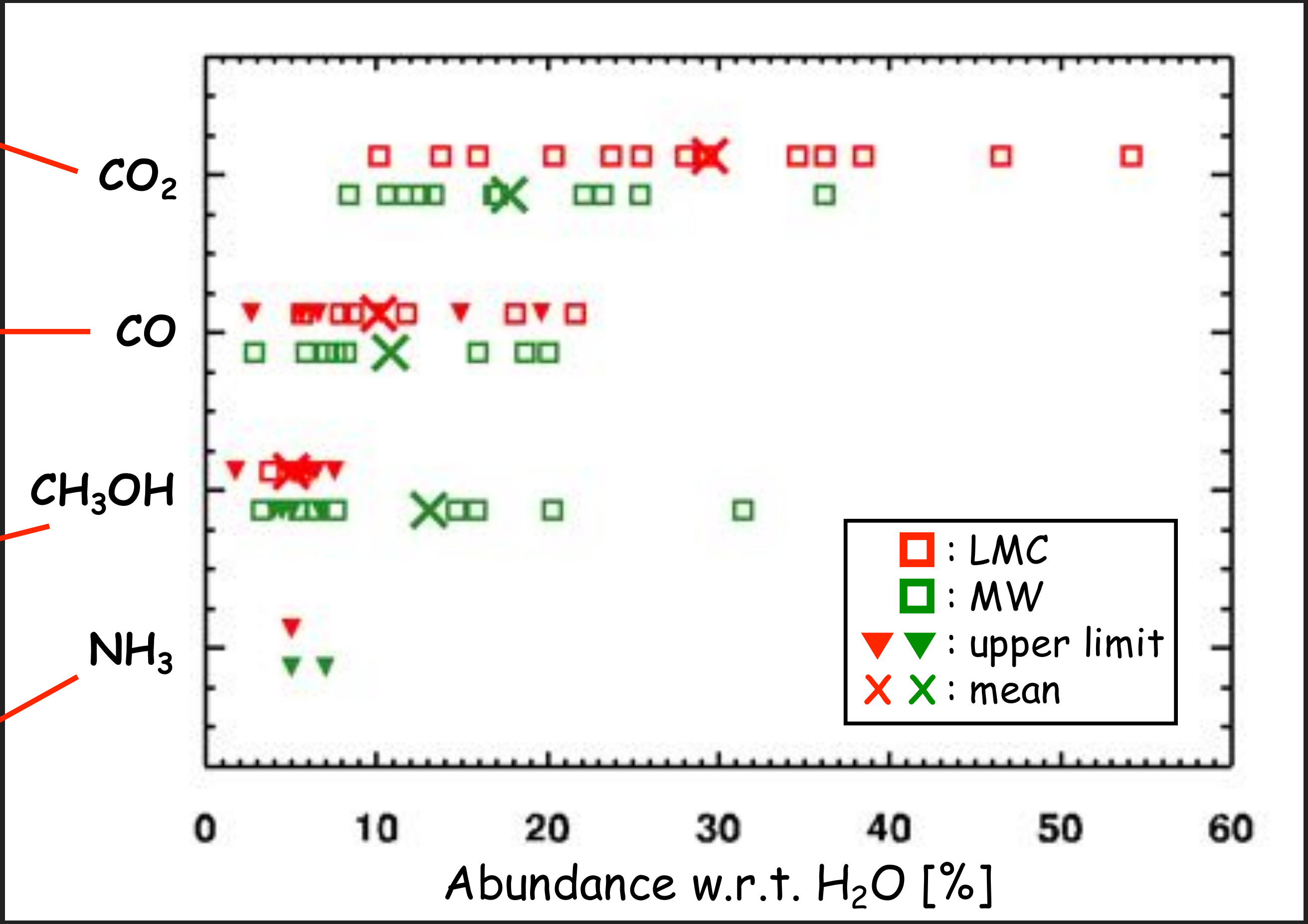


Fig.9 Comparison of ice compositions for LMC's and Galactic high-mass YSOs

Chemical compositions of ices in the SMC (1/5-1/10 lower metallicity)

- Similar between SMC and MW
- Very low abundance in SMC
- No data

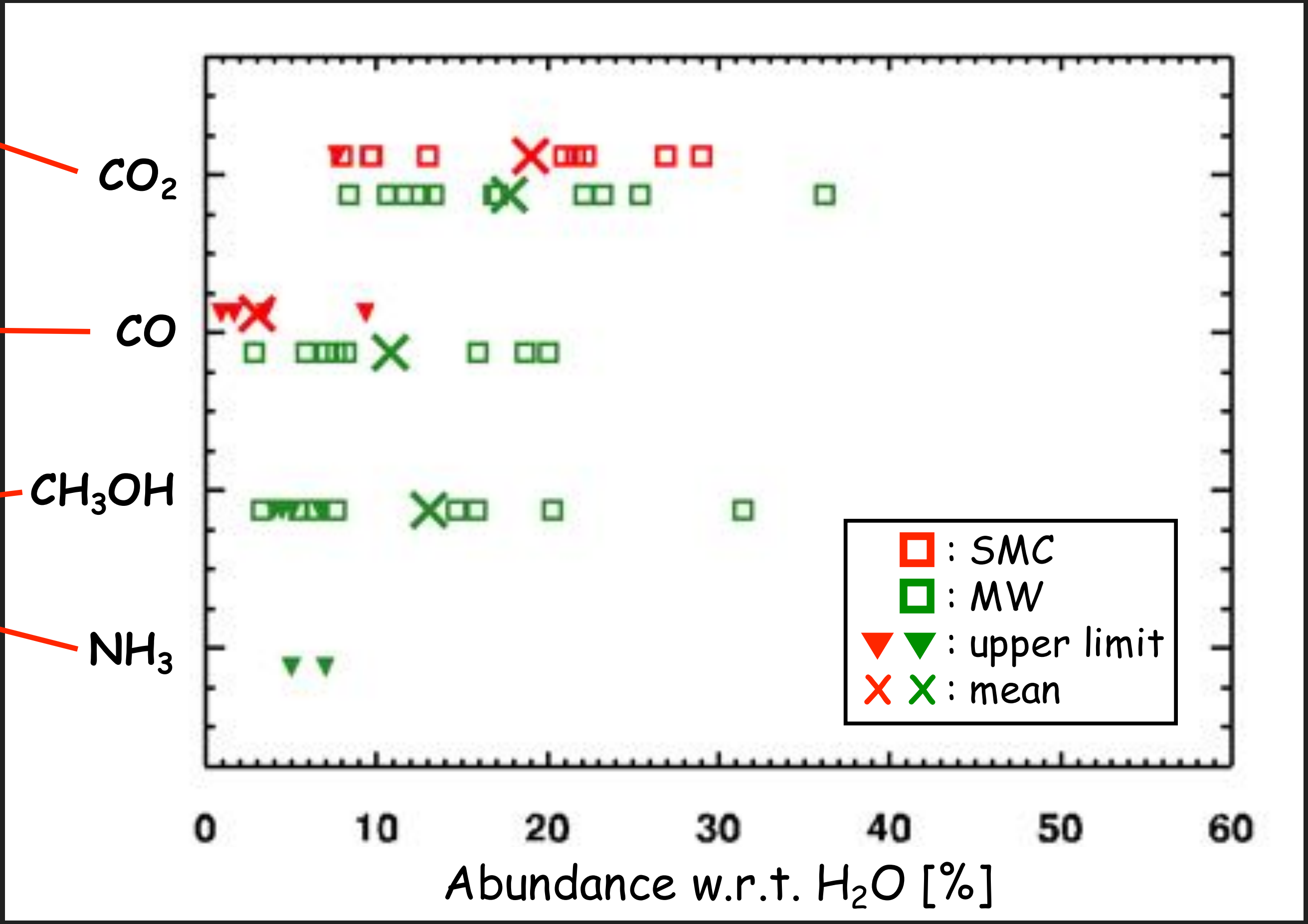


Fig.10 Comparison of ice compositions for SMC's and Galactic high-mass YSOs

Warm ice chemistry (see Shimonishi+ 2016a)

Low temperature (~10K)

Moderate temperature (<20K)

High temperature (>20K)

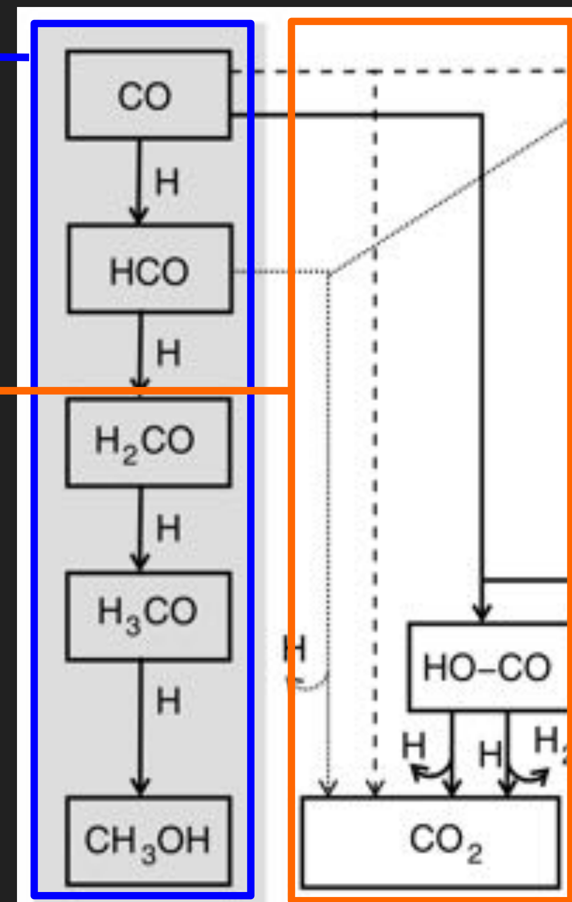


Fig.11 Up: Reaction pathway of CH_3OH and CO_2 formation on dust surface [Ioppolo+ 2011]. Left: Schematic image of warm ice chemistry.

Possible characteristics of ice chemistry as a function of galactic metallicity

- Grain surface chemistry at higher dust temperature is a key (Acharyya & Herbst, 2015, 2016; Shimonishi+ 2016a)

Similar CO ice abundance between LMC and MW

Or hydrogenation with an activation barrier

Table 2. Characteristics of ice chemistry in MW, LMC, and SMC

Galaxy	Metallicity	CO freeze-out	CO hydrogenation
Milky Way	~1	Yes	Yes
LMC	0.3-0.5	Yes	less efficient
SMC	0.1-0.2	No	No

Dust temperature

Low

↓

High

Absence of CO ice in SMC

Low CH_3OH abundance in LMC

Dust temperature vs. metallicity for extragalaxies

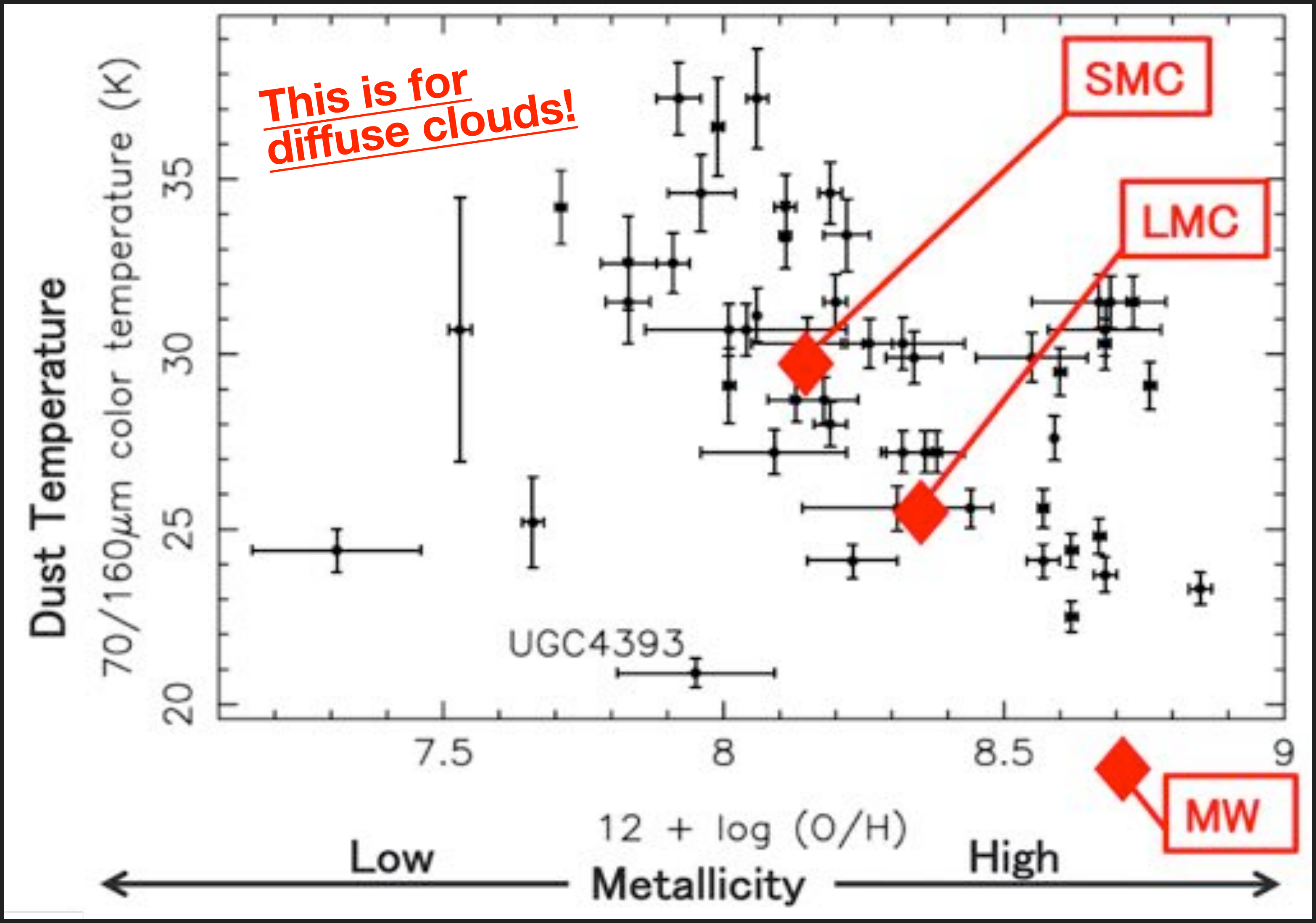
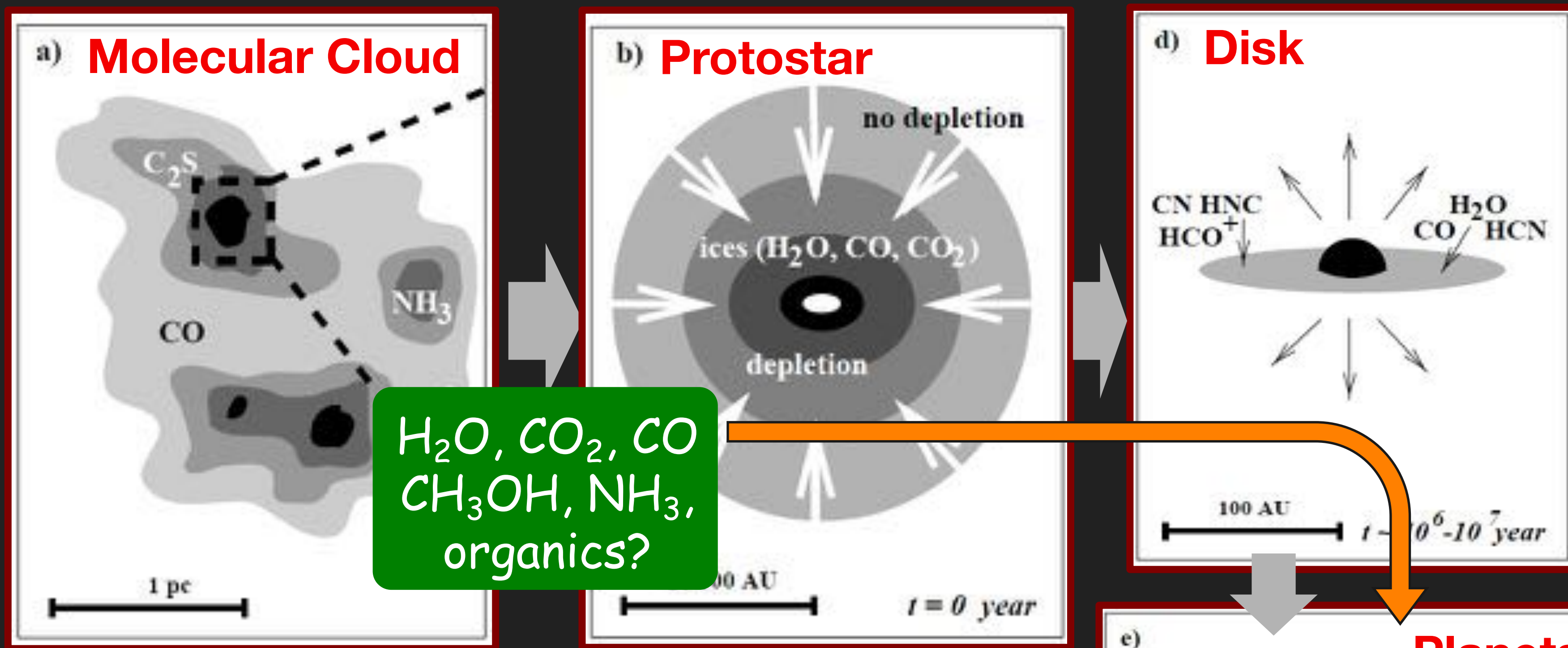
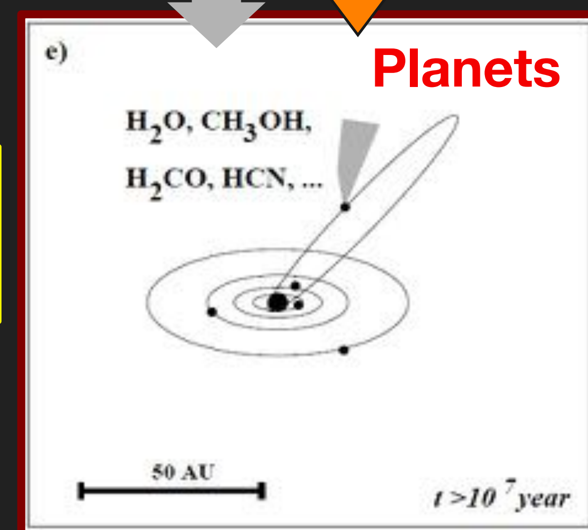


Fig.12 Far-infrared color temperature vs. metallicity for external galaxies [Engelbracht+ 2008]

Chemistry in star-/planet-forming regions





Metallicity affects the chemical processing of ices in star-forming regions.

Fig.13 Chemical evolution in star-forming regions [van Dishoeck and Blake, 1998]

Future: Next generation telescopes

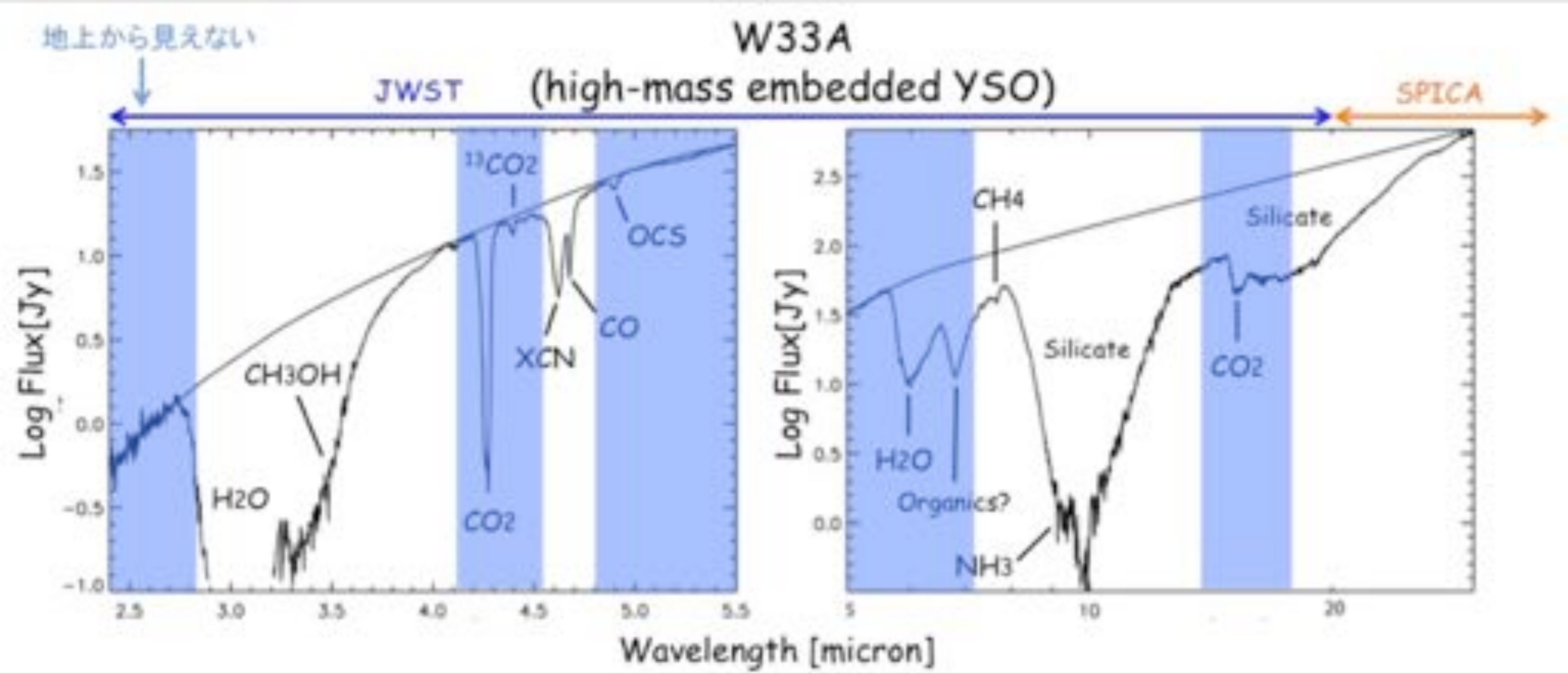


Fig.14 Wavelength coverage of spectrometers on JWST and SPICA.
Background is an infrared spectrum of a high-mass YSO W33A [Gibb+ 2004]

Observations of an extragalactic hot molecular core with ALMA

- Purpose: To understand the gas-grain chemistry in low-metallicity environments
- Target: a high-mass YSO, ST11, observed with *AKARI*
- Results: The first detection of an extragalactic hot core

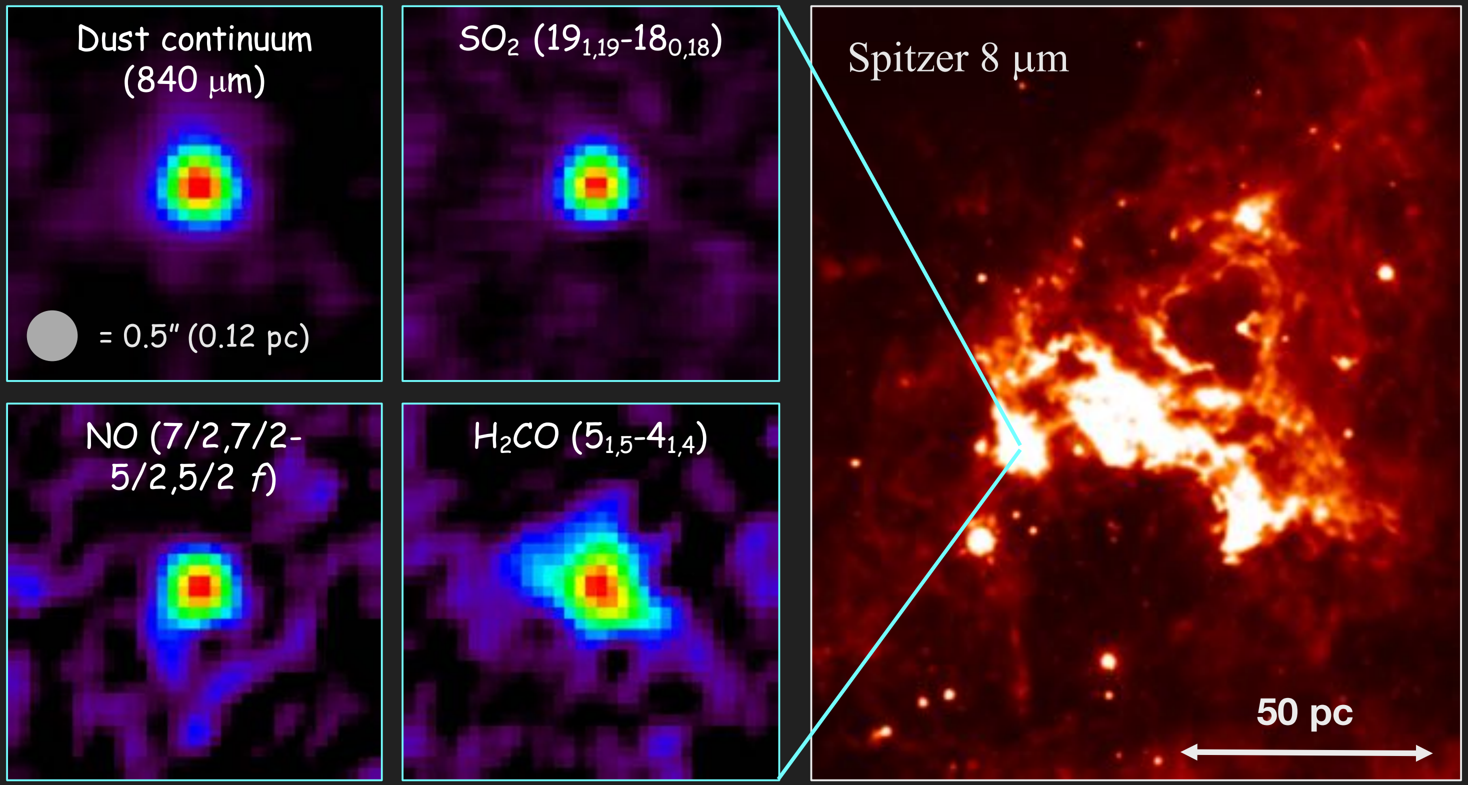
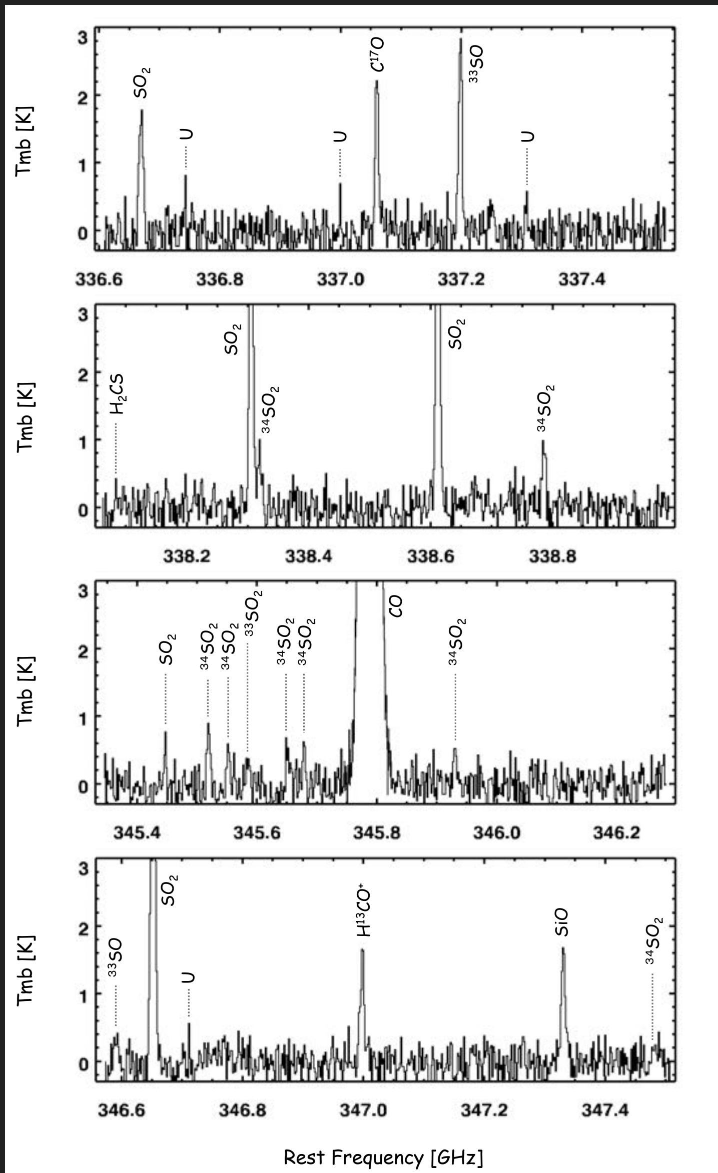
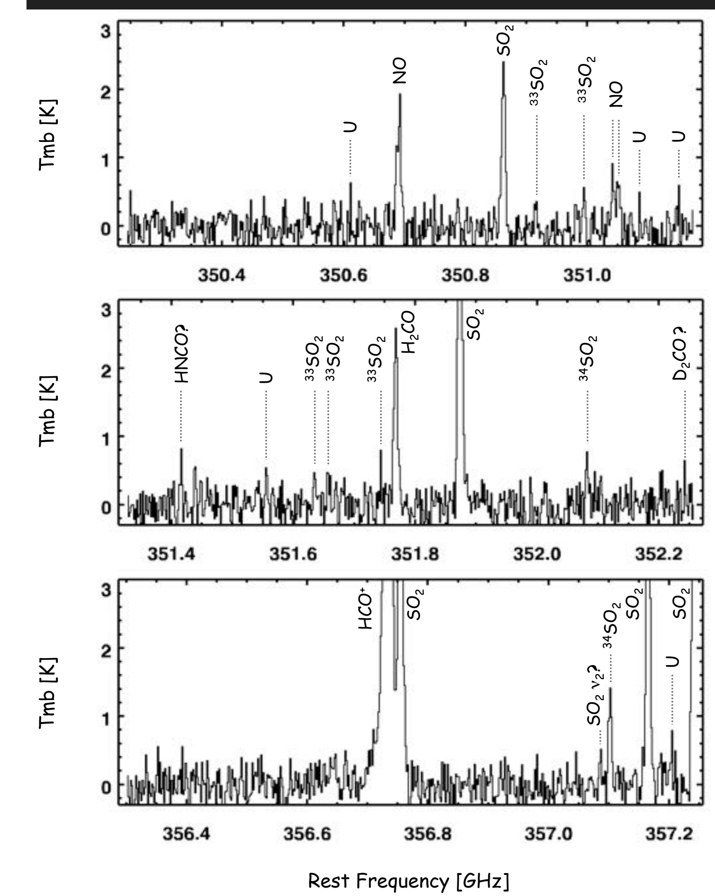


Fig.15 ALMA observations of a LMC high-mass YSO, ST11 [Shimonishi+ 2016b]

Molecular line emission from a LMC hot core

Detected molecules:
CO, $C^{17}O$, HCO^+, $H^{13}CO^+$, H_2CO, NO, SiO, H_2CS, ^{33}SO, $^{32}SO_2$, $^{34}SO_2$, and $^{33}SO_2$

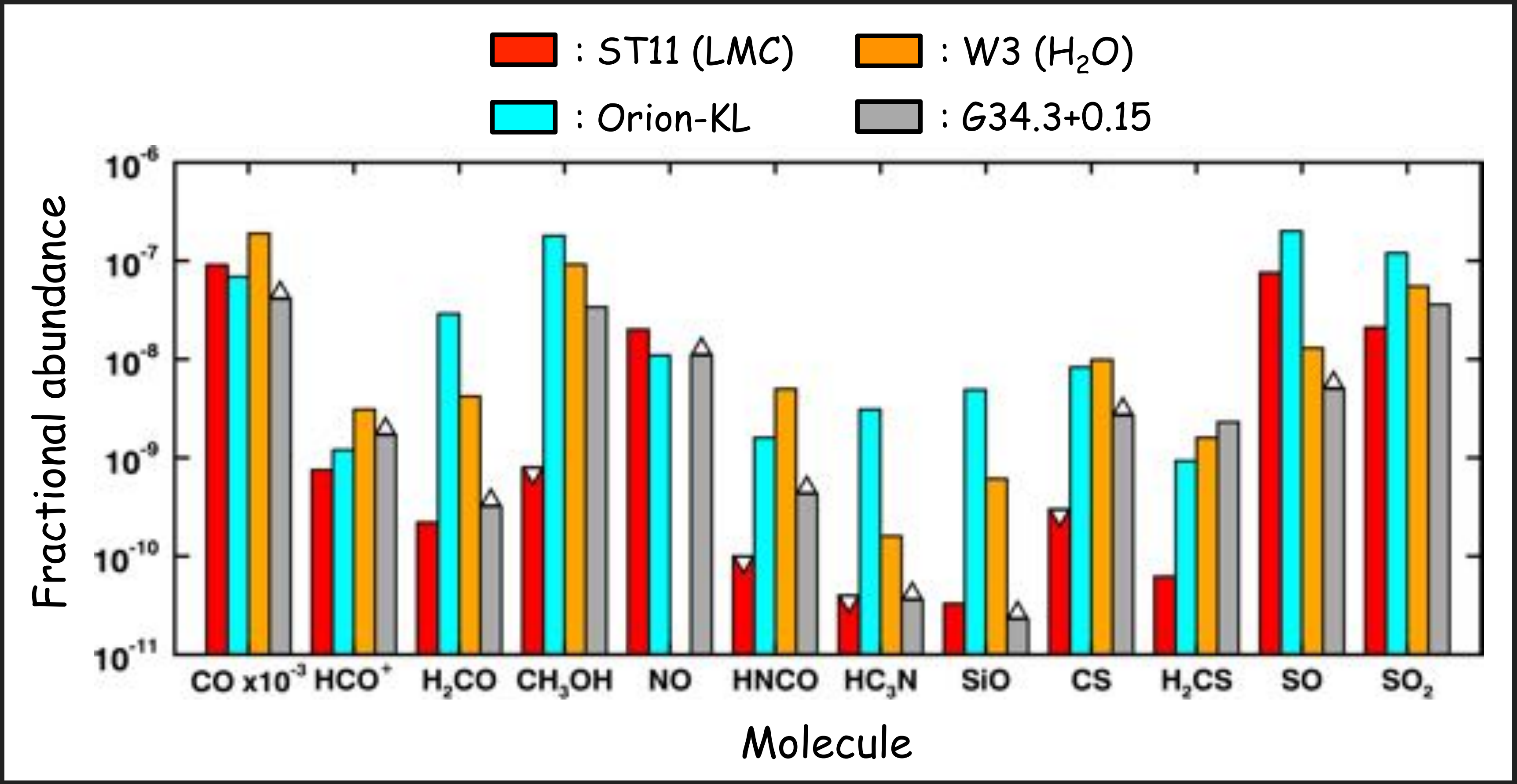




Spectra extracted from the central ~0.1 pc region

Fig.16 ALMA submili. spectra of ST11 [Shimonishi+2016b]

Molecular abundances of Galactic and extragalactic hot cores



- Optically thin and LTE assumption
- $N(H_2)$ from dust continuum
- T_{ext} = 100 K assumed except for SO_2

Fig.17 Comparison of molecular abundances for LMC and Galactic hot cores [Shimonishi+ 2016b]

まとめ

- 「あかり」により銀河系外の大質量YSOに付随する氷の観測が大きく発展した
- 結果として、低金属量環境下ではダスト表面反応の違いにより、原始星に付随する氷の化学組成が異なることが示唆された
- JWST, SPICAなどの次世代宇宙望遠鏡により大小マゼラン雲及び局所銀河群内の大・中・小質量YSOの氷・ダストの分光観測が可能になる

—サンプル天体数及び検出可能分子種の大幅な増加、中小質量YSOへの拡大など、飛躍的な研究の発展が見込まれる

- ALMA観測との連携により、固相・気相の両面から銀河系外原始星の化学組成を探ることが可能になりつつある