系外銀河における水・有機分子生成

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Ices in Space

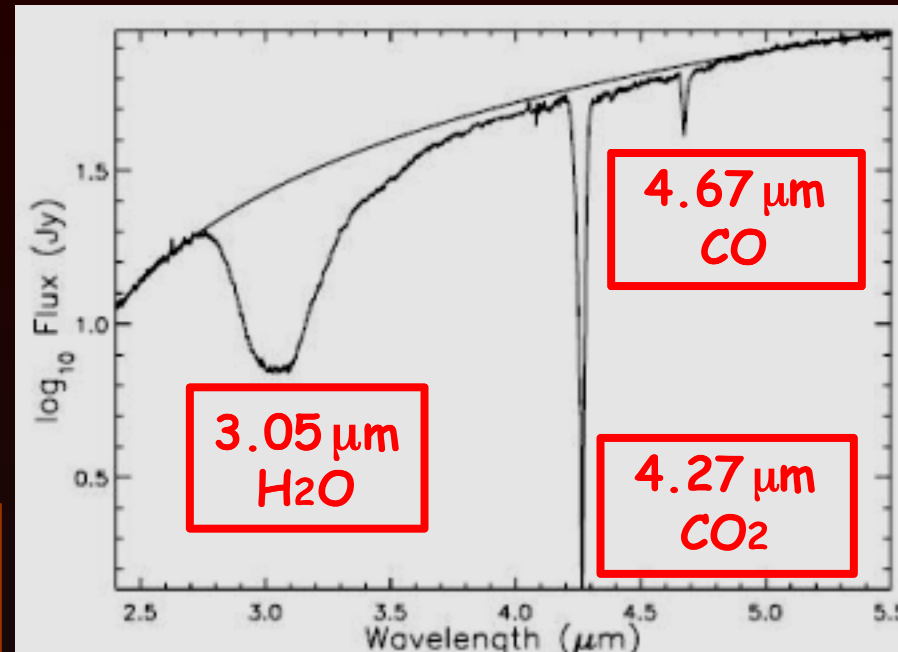


Fig.1 ISO-SWS spectrum of an embedded YSO AFGL989 [Gibb et al. 2004]

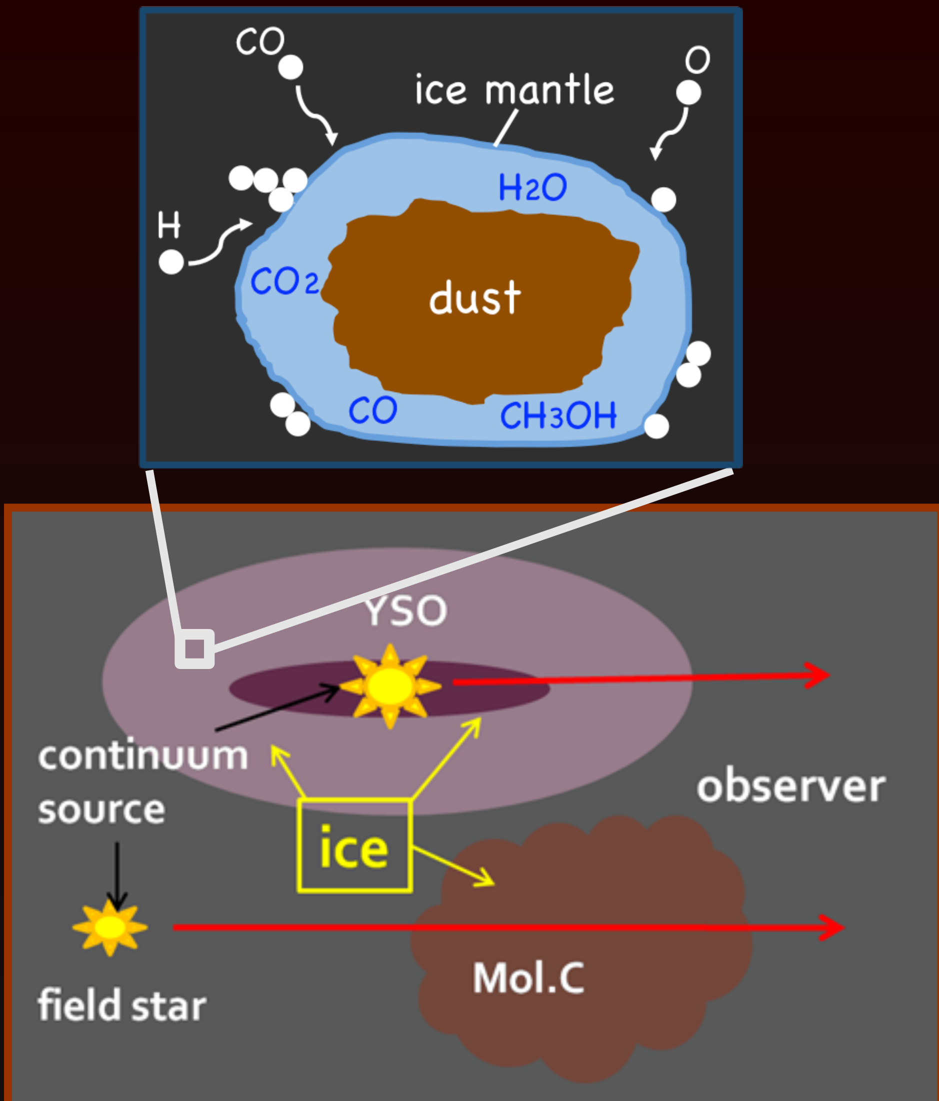


Fig.2 Ices in dense and cold molecular clouds

Interstellar ices and Comets

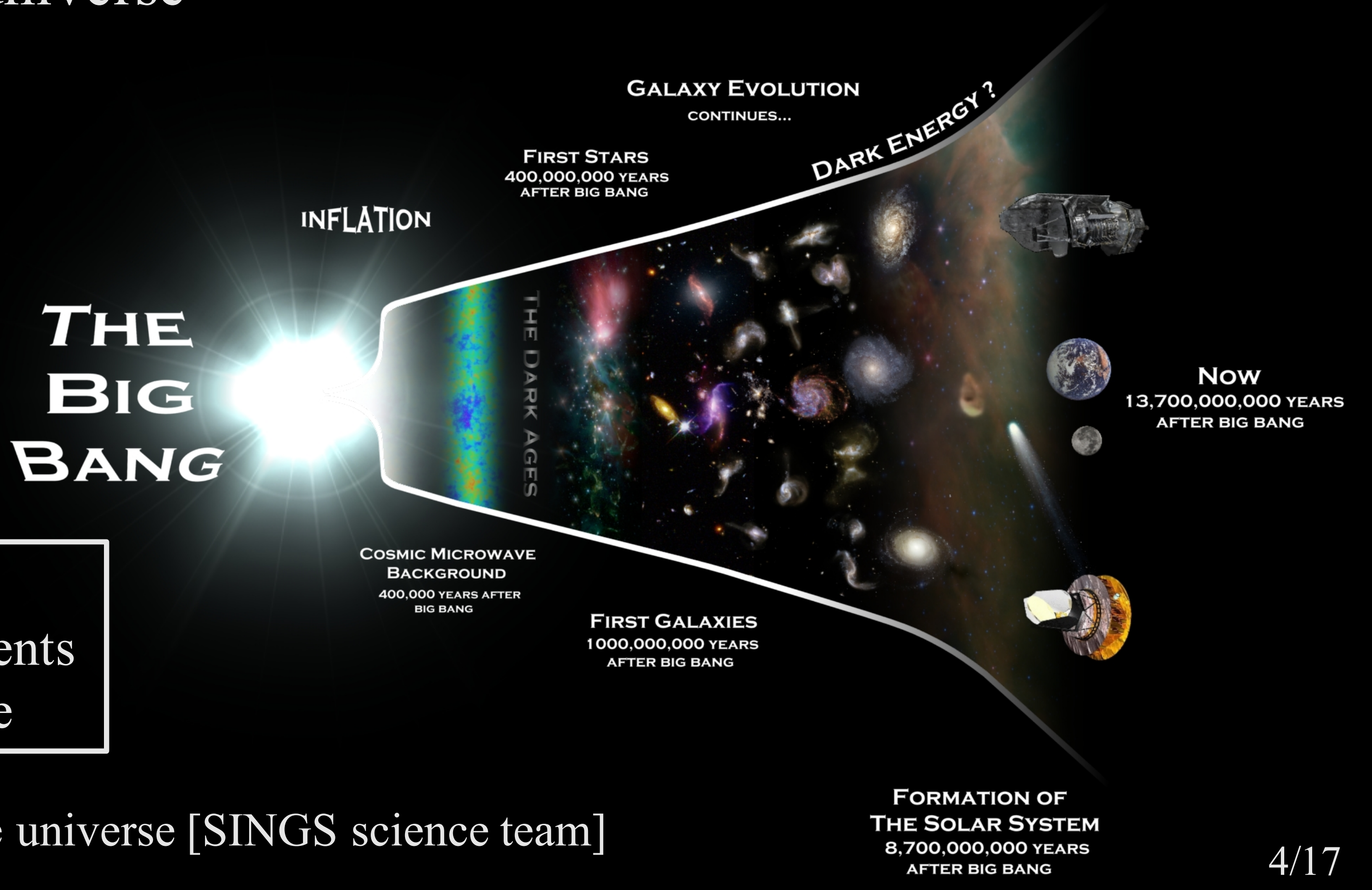
Table 1. Ice abundances toward various astronomical objects [Boogert+ 2015]

Molecule	Abundance w.r.t. H_2O ice			
	High-mass protostars	Low-mass protostars	Molecular clouds	Comets
H_2O^e	100	100	100	100
CO^e	7_{4}^{15} (7) 3–26	21_{12}^{35} (18) (<3)–85	25_{20}^{43} 9–67	nd 0.4–30
$CO_2{}^e$	19_{12}^{25} 11–27	28_{23}^{37} 12–50	26_{18}^{39} 14–43	15_{10}^{24} 4–30
CH_3OH	9_{5}^{23} (5) (<3)–31	6_{5}^{12} (5) (<1)–25	8_{6}^{10} (6) (<1)–12	nd 0.2–7
NH_3	nd $\sim 7^f$	6_{4}^{8} (4) 3–10	nd <7	nd 0.2–1.4
CH_4	nd 1–3	4.5_{3}^{6} (3) 1–11	nd <3	nd 0.4–1.6

Notes. The first row is median and upper/lower quartile values.
The second row is the full range of measured abundances.

Extragalactic Astrochemistry

- How do environmental characteristics of galaxies affect chemical properties of interstellar medium?
- Low metallicity galaxies are a key to understand chemistry in the past universe



Metal (astronomy):
All the heavy elements other than H and He

Fig.3 Evolution of the universe [SINGS science team]

The Large Magellanic Cloud

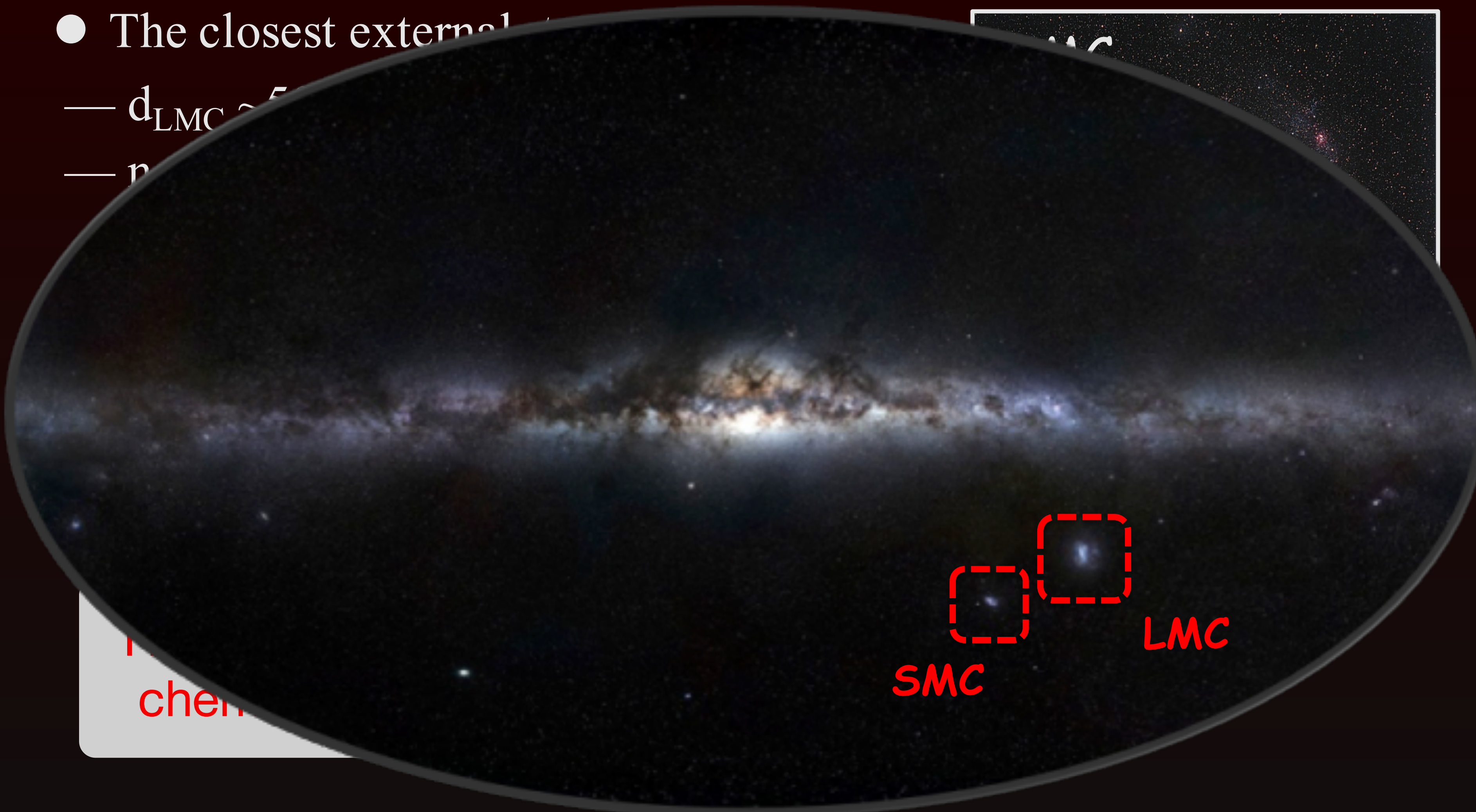
- The closest externa

— $d_{LMC} \sim$

— n

r

chen



[1]Pietrzyn ´ ski+ 2013, [2]Westerlund, 1990, [3]Luck et al. 1998
[4] e.g., Hopkins & Beacom 2006, Rafelski et al. 2012

Observations of Ices in Magellanic Clouds

Fig.5 (right) Infrared spectrum of a high-mass YSO in the LMC

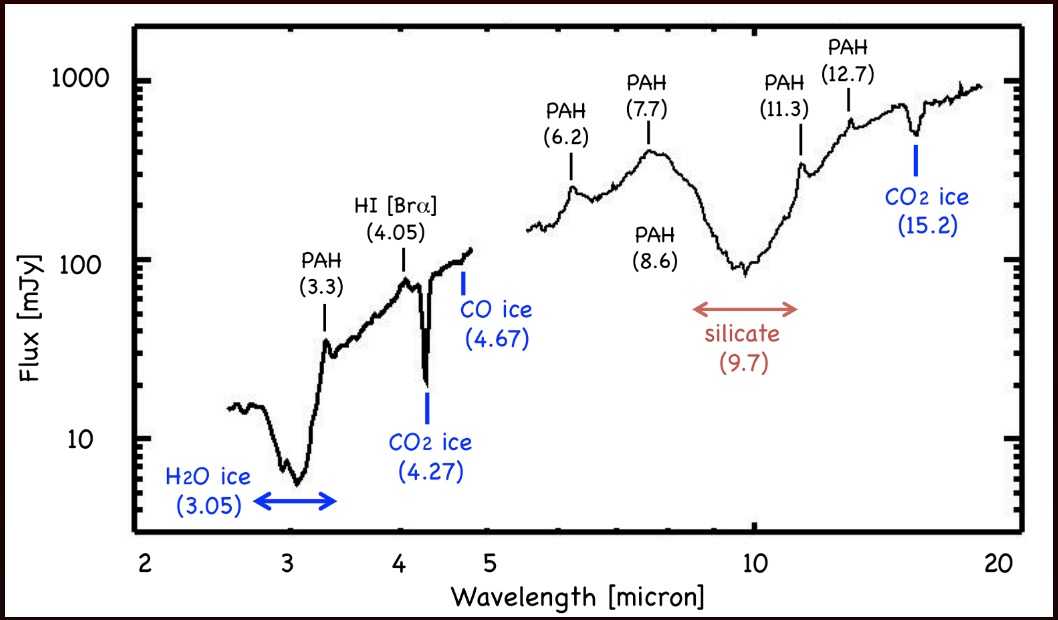
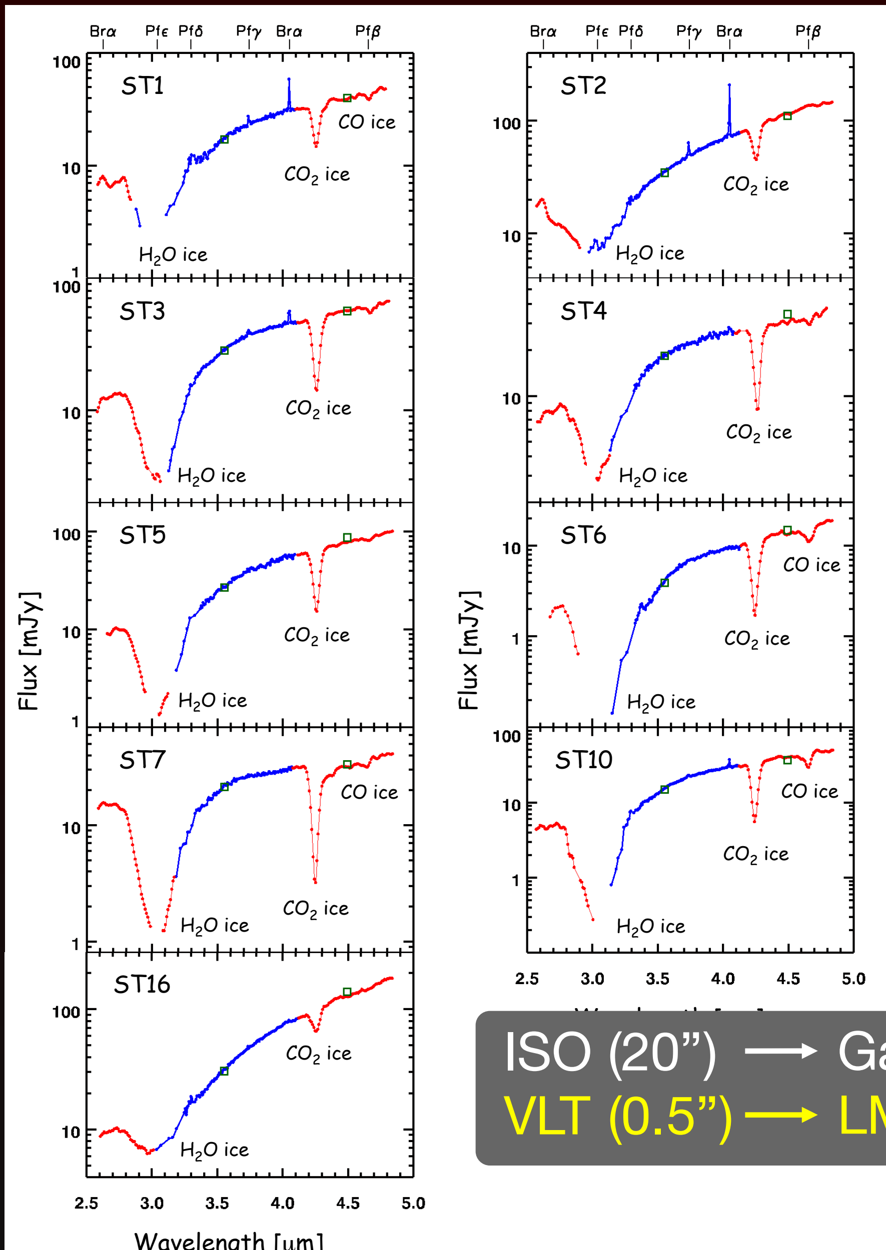
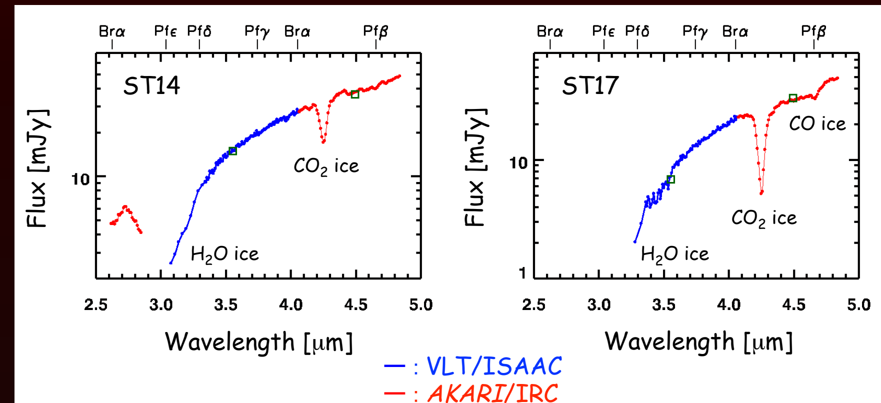


Table.2 Summary of ice detections toward high-mass YSOs in the Magellanic Clouds

λ [μm]	Cloud	No.	Ice band	References
2-5 (AKARI, VLT)	LMC	16	H_2O, CH_3OH, CO_2, CO, (XCN)	Shimonishi+ 2008, 2010, 2012, 2013, 2016; van Loon+ 2005; Oliveira+ 2006, 2011
	SMC	12	H_2O, CO_2, CO	van Loon+ 2008; Oliveira+ 2011, 2013; Shimonishi+ 2012
5-20 (Spitzer)	LMC	41	(H_2O), CO_2, (NH_3)	van Loon+ 2005; Oliveira+ 2009, 2011; Seale+ 2009, 2011; Shimonishi+ 2016
	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

IR Spectra of High-mass YSOs in LMC





- VLT/ISAAC + *AKARI*/IRC spectra

—2.6~4.9 μm, R ~500 (VLT)

- 11 high-mass YSOs

—$L_{target} = 10^4$–10^5 $L_\odot$

—9 observed*, 2 from archive

*090.C-0497, PI: E. Dartois

ISO (20”) ⟶ Galactic HMYSOs (~1 kpc) ⟶ ~0.1 pc

VLT (0.5”) ⟶ LMC sources (50 kpc) ⟶ ~0.1 pc

[Shimonishi et al., A&A, 2016]

Fitting Water Ice Band

- Well fitted by amorphous water ice as well as Galactic sources

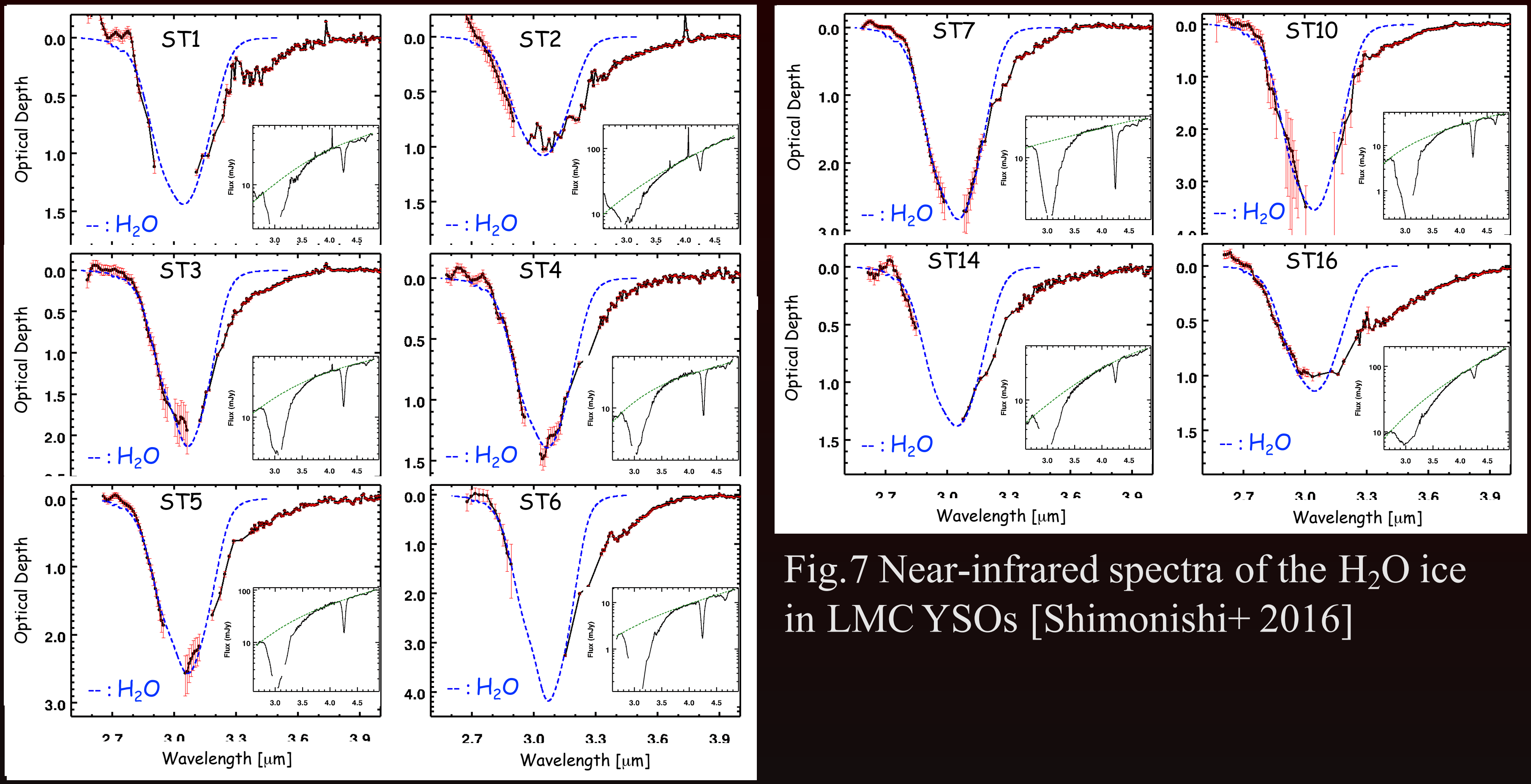
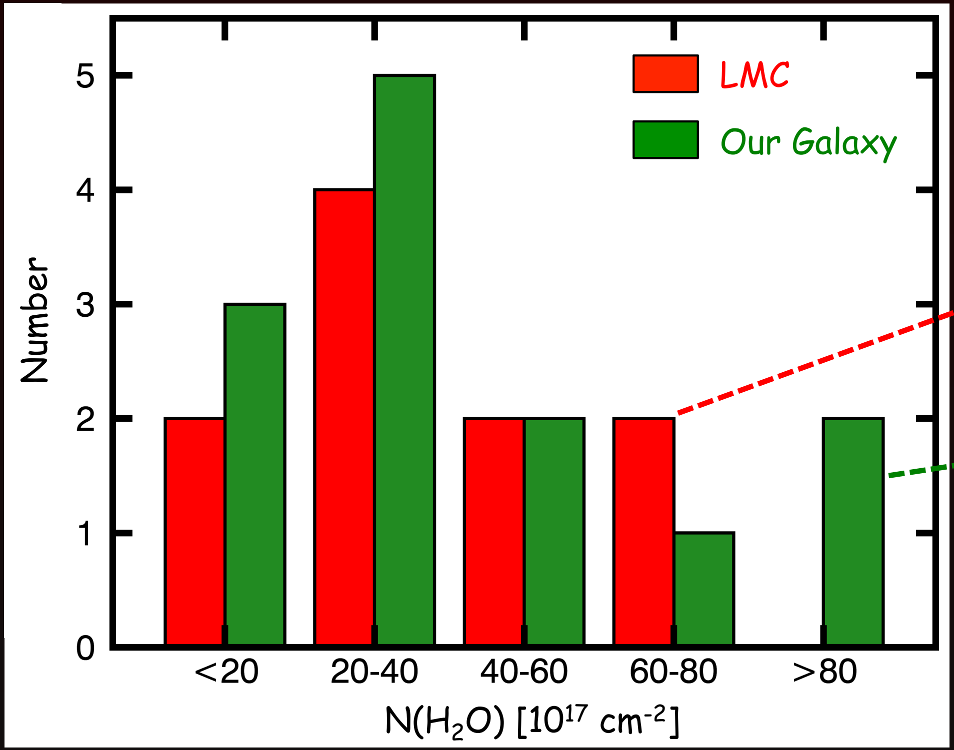


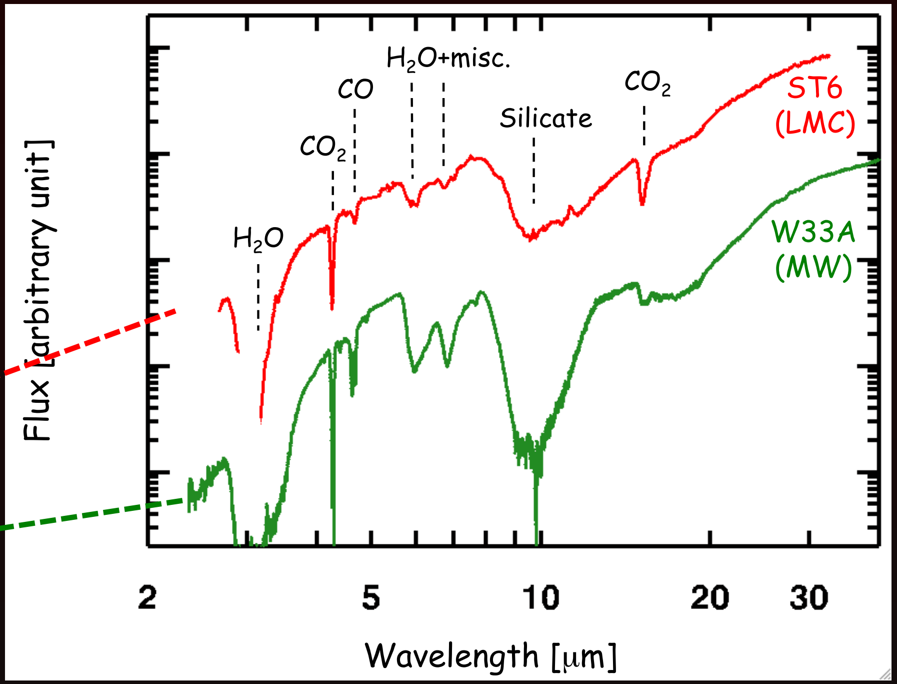
Fig.7 Near-infrared spectra of the H_2O ice in LMC YSOs [Shimonishi+ 2016]

Water Ice in the LMC

- Similar distribution of H_2O ice column densities for Galactic and LMC high-mass YSOs
- However, we lack extremely embedded sources in the LMC



Very embedded sources



LMC: Shimonishi+ 2016

MW: Gibb+ 2004; Boogert+ 2008

Fig.8 Histogram of water ice column densities for LMC and Galactic high-mass YSOs

Fitting Methanol Ice Band

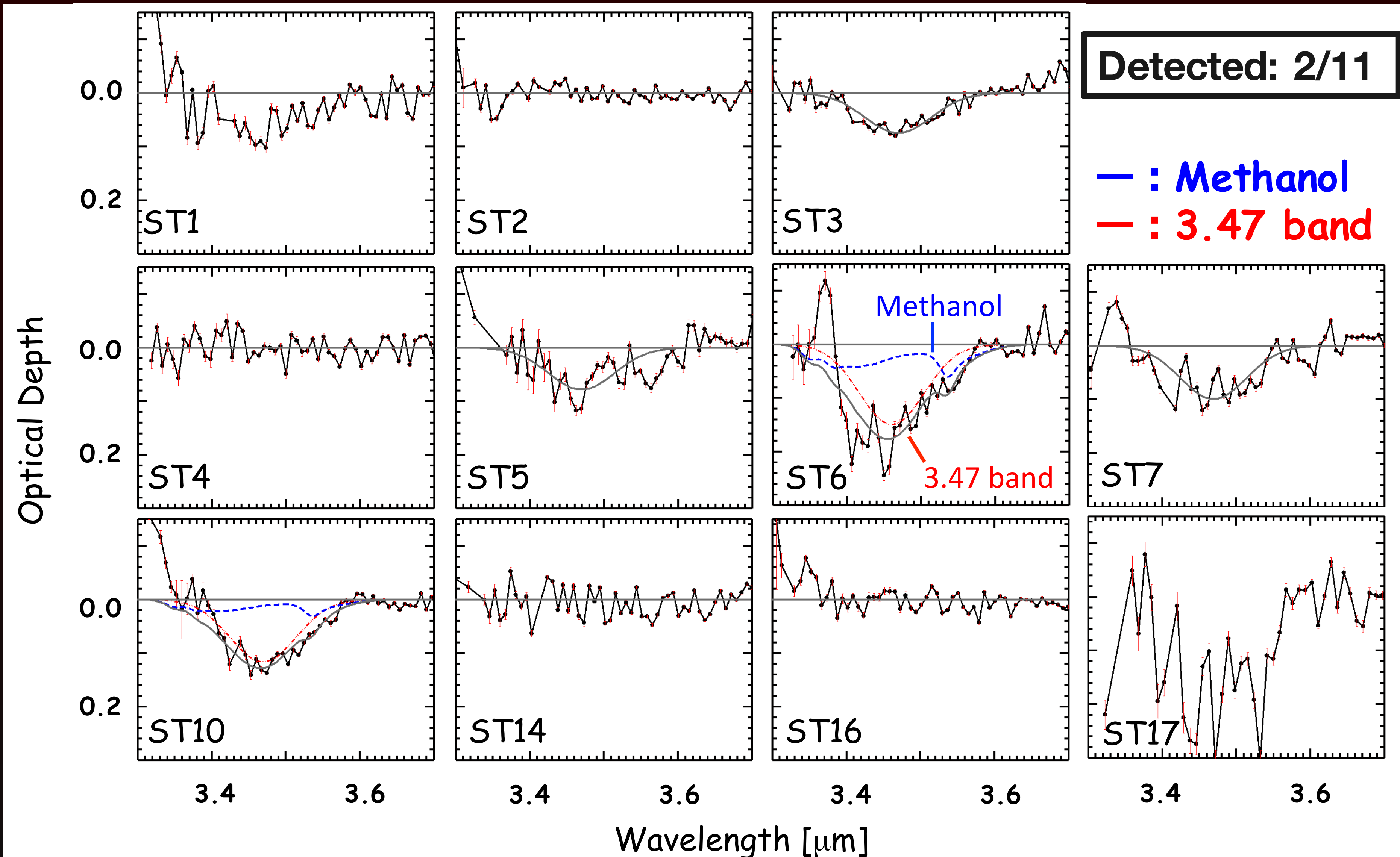
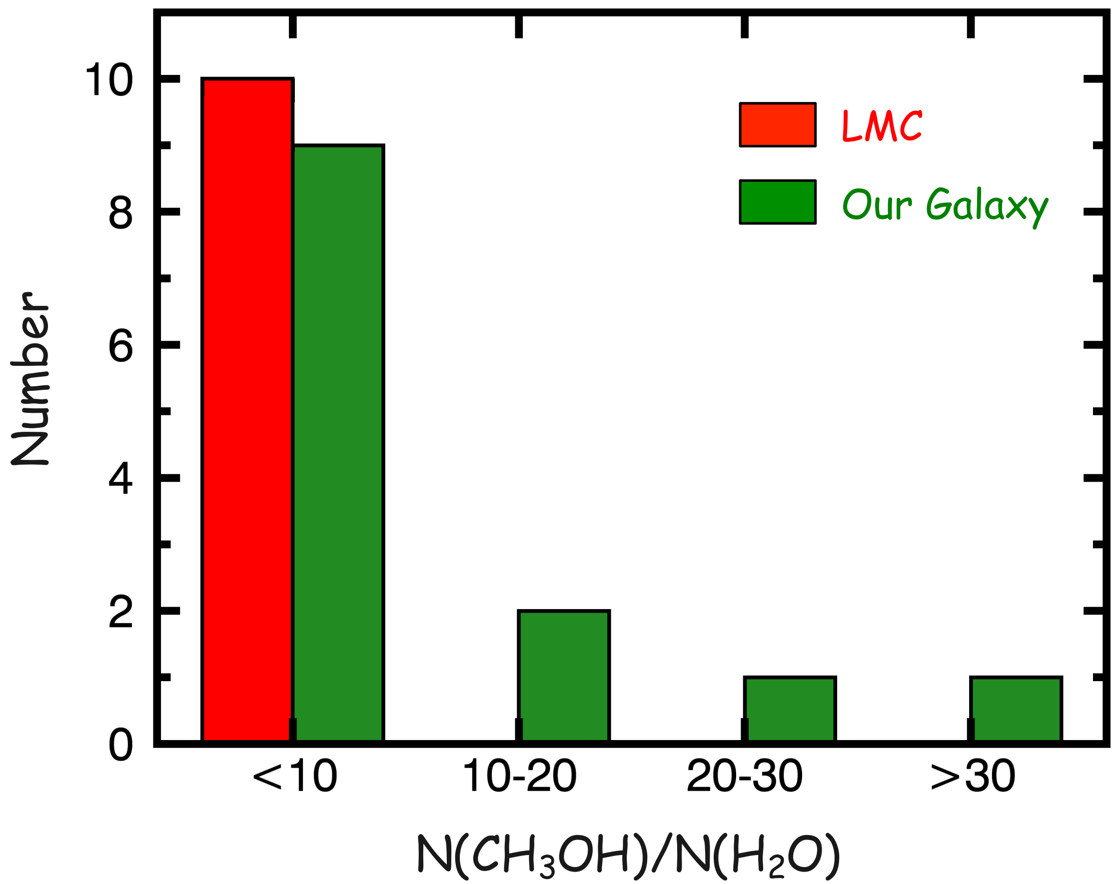


Fig.9 Near-infrared spectra of the CH_3OH ice in LMC YSOs [Shimonishi+ 2016]

Methanol ice in the LMC

- Methanol ice is less abundant in the LMC



LMC: Shimonishi+ 2016, MW: Brooke+ 1999; Dartois+ 1999

Fig.10 Histogram of methanol ice abundances for LMC and Galactic high-mass YSOs [Shimonishi+ 2016]

Table 3. CH_3OH ice abundances in the LMC

Source	$N(CH_3OH)/N(H_2O)$ (%)
ST1	<4.8
ST2	<6.4
ST3	<1.7
ST4	<5.2
ST5	<5.7
ST6	5.6
ST7	<4.8
ST10	3.7
ST14	<7.6
ST16	<6.1

Methanol gas in the LMC

- Underabundant detections of methanol masers in the LMC (e.g., Green+ 2008, Ellingsen+ 2010)

—Only 4 CH_3OH maser sources out of 16 H_2O maser sources

- Weak/absent emission of thermal CH_3OH lines in star-forming regions in the LMC (Nishimura+ 2016, Shimonishi+ in prep.)

→ Suggesting low abundance of methanol gas in the LMC

A hot molecular core in the LMC

- Source size ~0.1 pc
- T_{gas} ~100-200 K from SO_2 and $^{34}SO_2$
- $n(H_2)$ >2 x 10^6 from dust continuum
- Protostar ~5 x 10^5 $L_\odot$

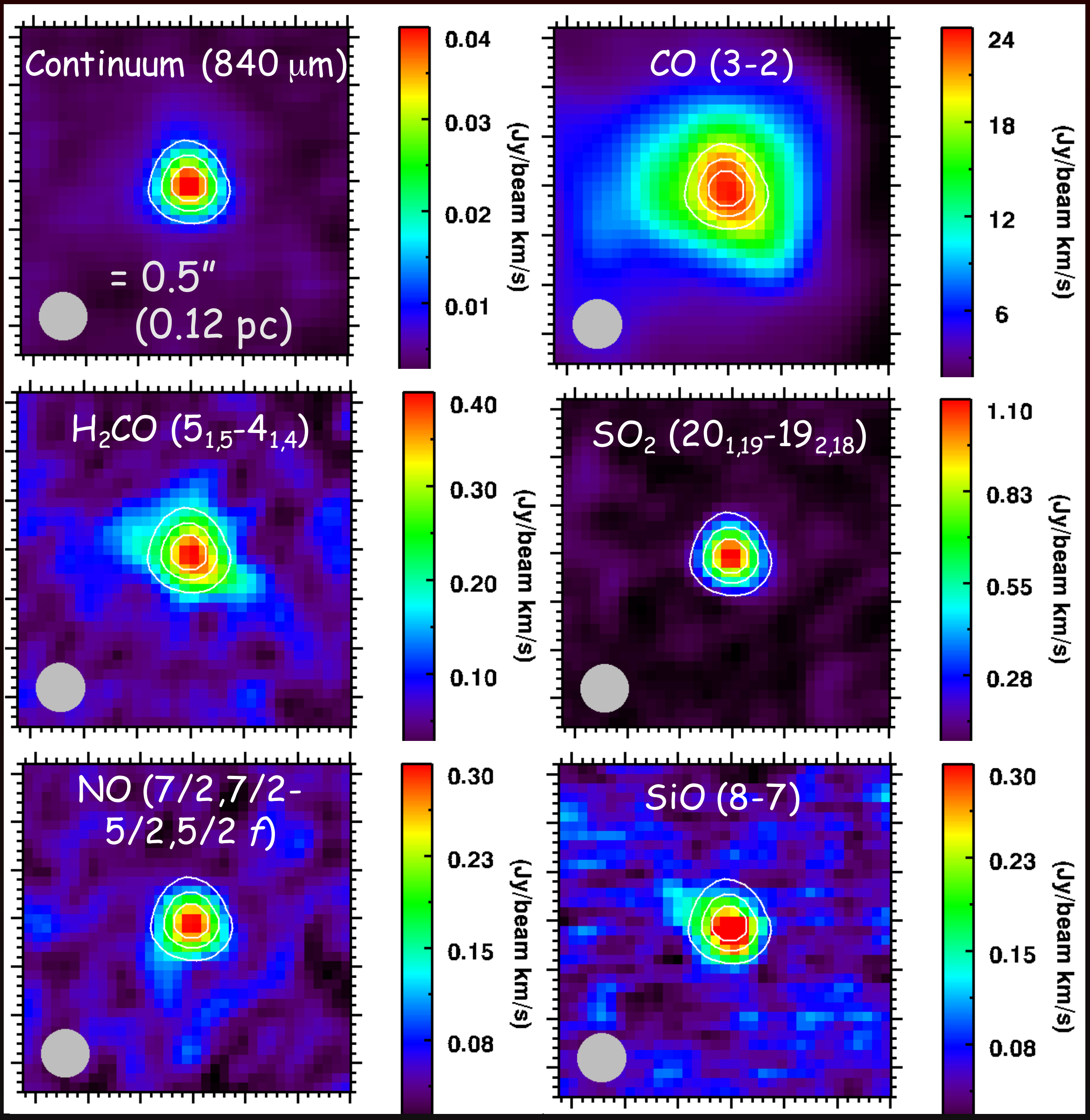


Fig.12 ALMA Band 7* (345 GHz) images of emission from ST11 [Shimonishi+ submitted]

*Cycle 1 (PI T. Shimonishi)

Deficiency of CH_3OH, H_2CO, and HNCO in the LMC hot core

- Less abundant by 1–3 orders of magnitude than Galactic hot cores

cause →

Warm ice chemistry in the LMC (Shimonishi+ 2016)
—Suppressed hydrogenation of CO on grain surfaces due to high dust temperatures

(See also Acharyya & Herbst 2015, Watanabe+ 2003)

Tab 4. Comparison of abundances w.r.t. H_2

Molecule	ST11 (LMC)[a]	Galactic hot cores[b]
CH_3OH	$<8 \times 10^{-10}$	$10^{-8} – 10^{-6}$
H_2CO	2.2×10^{-10}	$10^{-9} – 10^{-8}$
HNCO	$<1 \times 10^{-10}$	$10^{-9} – 10^{-8}$

[a]Shimonishi+ submitted; [b]Sutton+ 1995; Schilke+ 1997; Helmich & van Dishoeck, 1997; MacDonald+ 1996; Thompson & MacDonald 1999

Chemical properties of ices in the LMC

Consistent with numerical simulation by Acharyya & Herbst 2015

Due to increased mobility of CO at high dust temperature, which enhance CO + OH → CO_2.

Due to suppressed hydrogenation of CO.

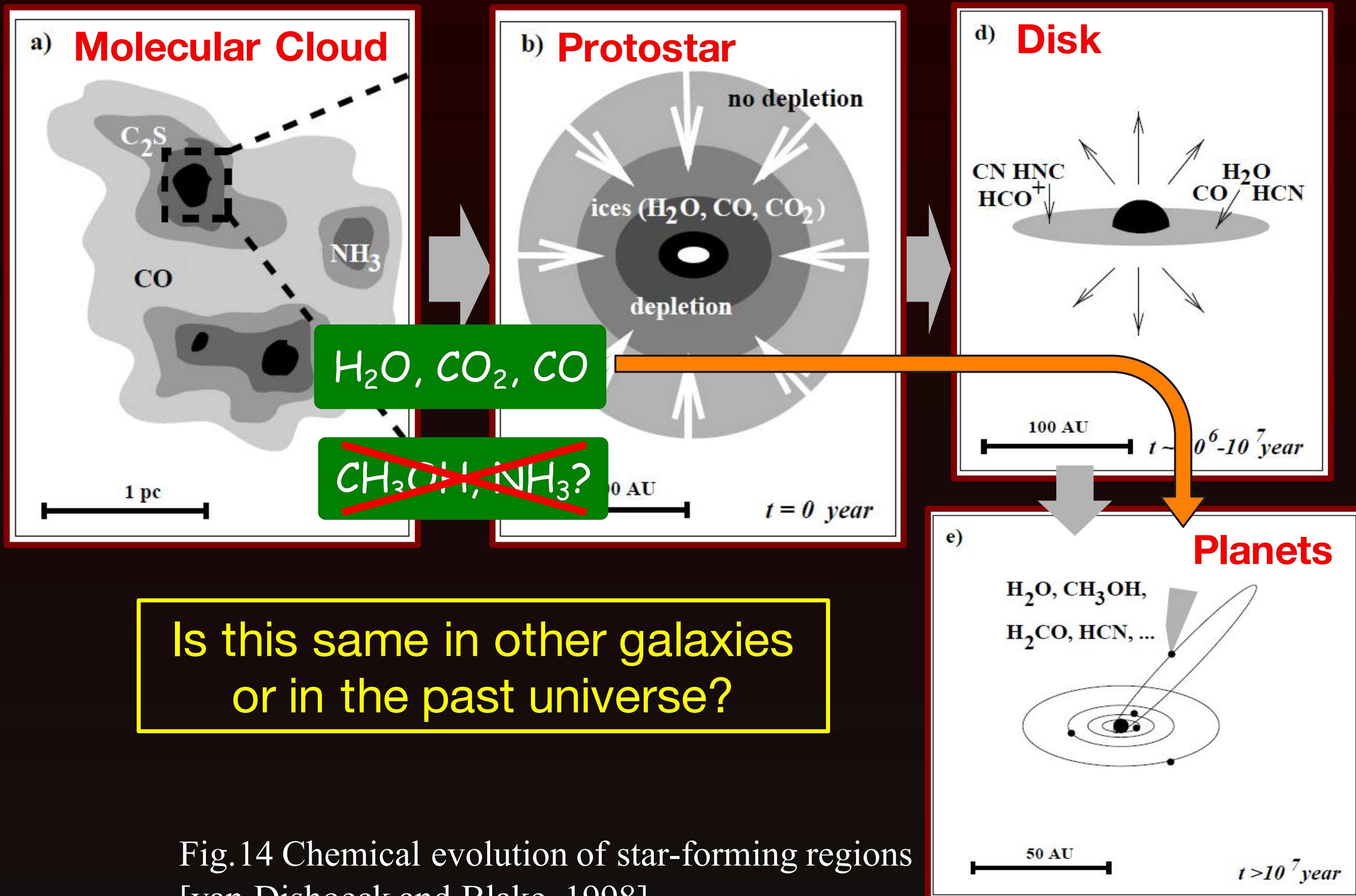
Table 5. Comparison of ice abundances for LMC and Galactic high-mass YSOs

Molecule	Characteristics: LMC vs. MW
H_2O	No extremely embedded source in LMC[1].
CO_2/H_2O	About 2 times higher in LMC[1,2].
CO/H_2O	Similar in LMC[1].
CH_3OH/H_2O	Deficient in LMC, both for ice[1] and gas[3,4]
NH_3/H_2O	Only weak upper limit on ice[1], but gas is underabundant by ~2 orders of magnitude[5].

*<5% for one LMC source[1]

Ref. [1]Shimonishi+ 2016; [2]Shimonishi+ 2010
[3]Shimonishi+ submitted; [4]Nishimura+ 2016; [5]Ott+ 2010

Water and Organics in low metallicity galaxies



Is this same in other galaxies
or in the past universe?

Fig.14 Chemical evolution of star-forming regions
[van Dishoeck and Blake, 1998]

まとめ

- 赤外線及び電波観測により、低金属量銀河「大マゼラン雲」にある大質量原始星周囲の氷・分子ガスの化学組成を調査した

- 水は低金属量銀河でも存在するが、銀河系内で見つかっている極端にダストに埋もれた原始星は未だ見つかっていない

- メタノールは、低金属量環境では固相でも気相でも欠乏している

— ダスト表面反応の違いが原因 (Warm Ice Chemistry)

- 有機分子も欠乏している可能性はあるが、さらなる調査が必要

— 過去の宇宙は無機質な世界か?

- 今後

— JWST・SPICAによる大規模な銀河系外氷天体サンプルの観測

— ALMA Cycle 3 スペクトルサーベイによる低金属量ホットコアの有機分子の調査

Backup

Dust temperature vs metallicity for extragalaxies

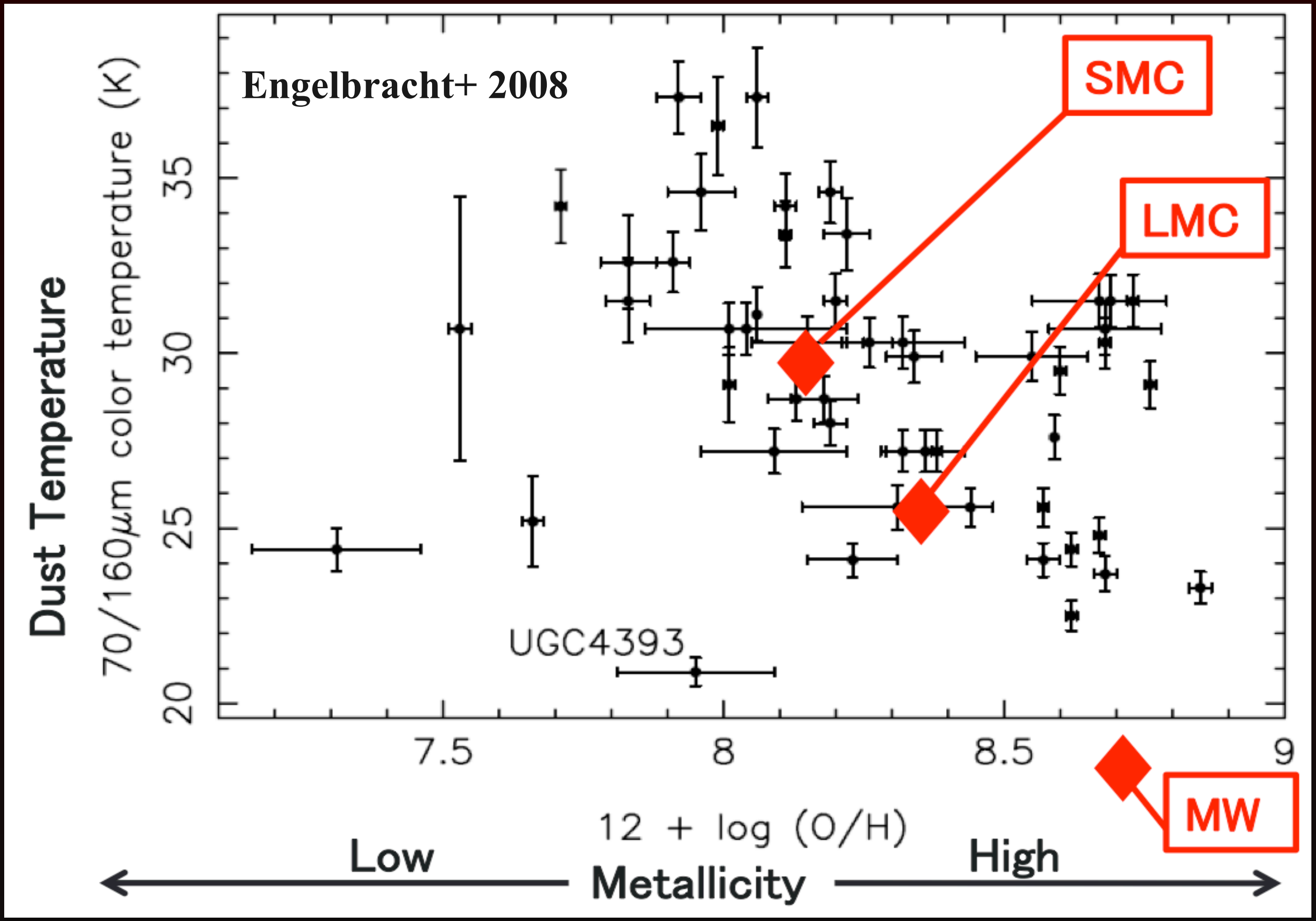
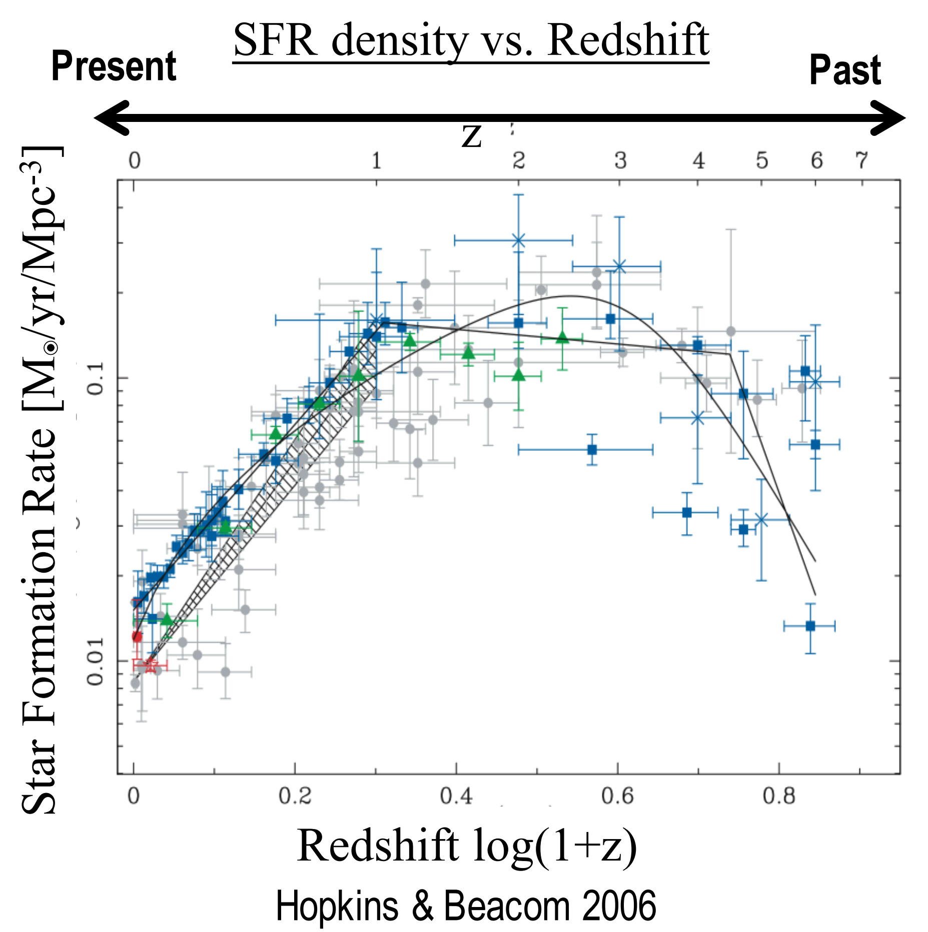


Fig.15 Far-infrared color temperature vs. metallicity for external galaxies

Magellanic Clouds in a Cosmological Context

- Metallicity of the LMC/SMC is close to the cosmic metallicity during the epoch of peak star formation (z ~1–2)



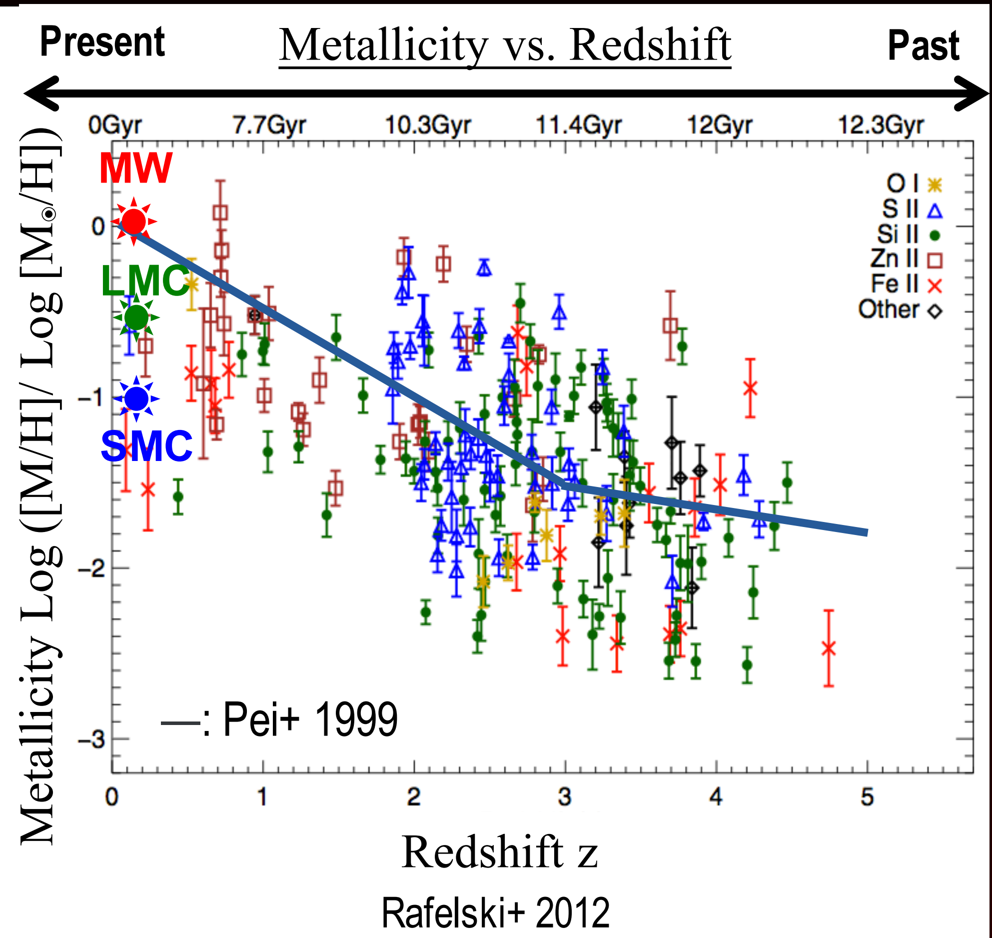


Fig.16 Redshift vs. specific star-formation rate (left) and redshift vs. metallicity (right)

High CO_2 ice abundance in the LMC

□ : LMC's YSO[1]
■ : MW's YSO[2]

1. Shimonishi+2010
2. Gibb+ 2004

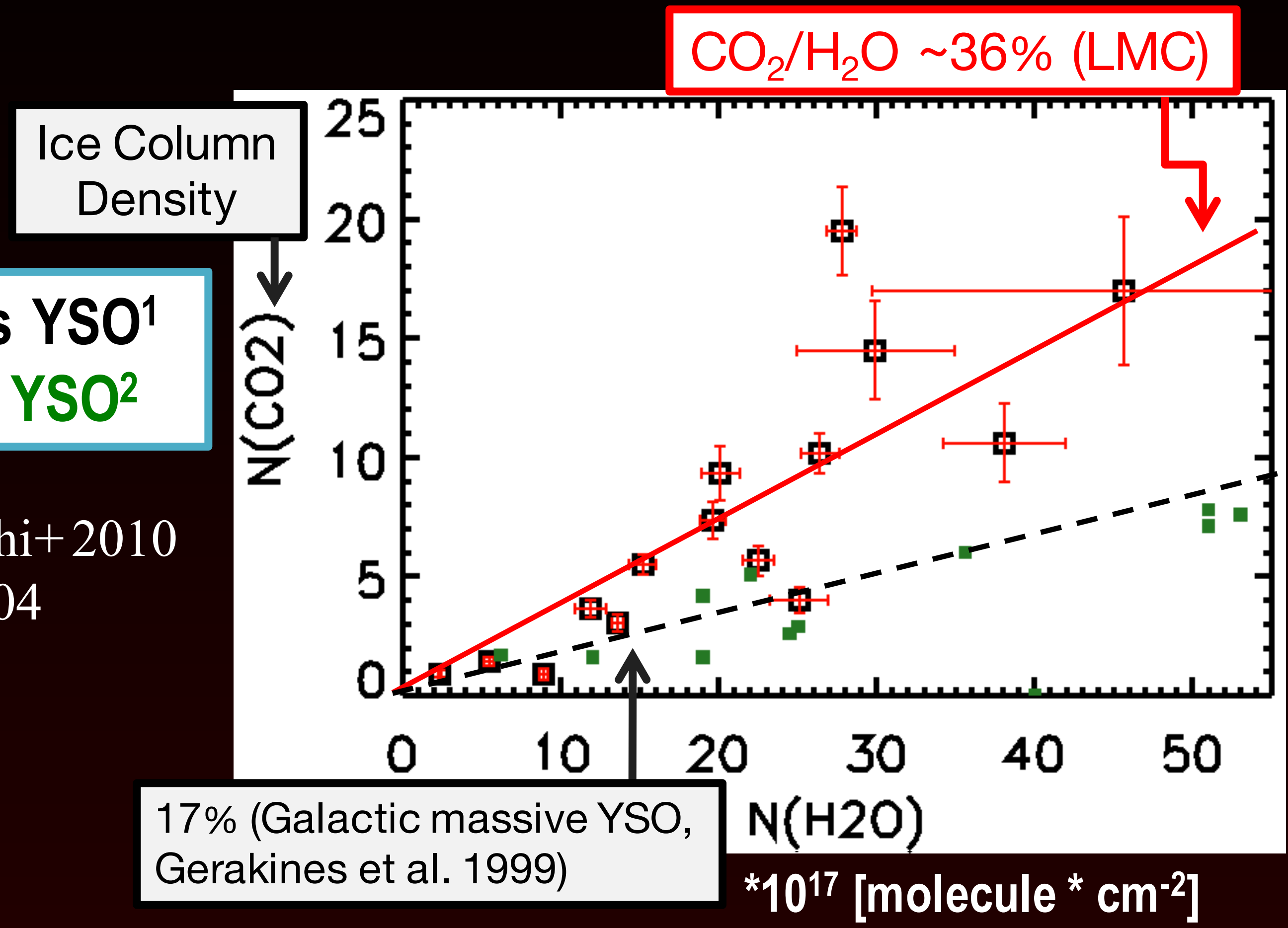


Fig.17 H_2O ice vs. CO_2 ice column density