赤外線観測で探る銀河系外の原始星の星周物質

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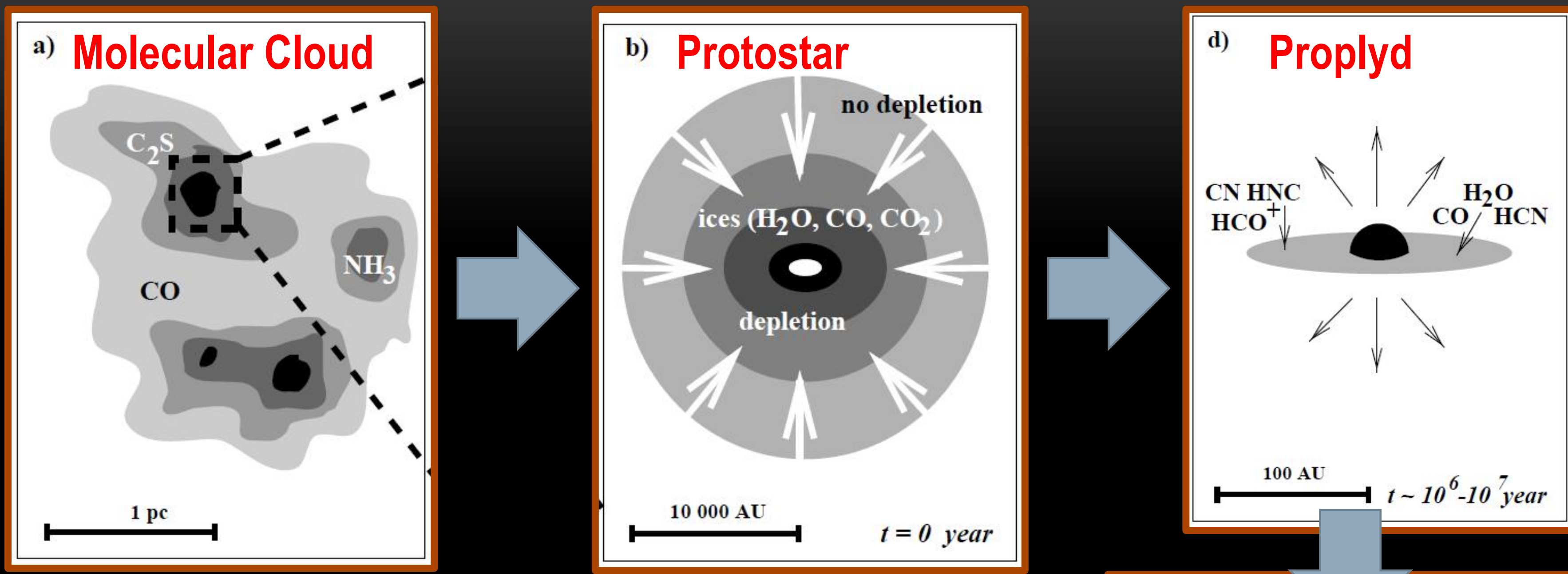
Outline

1. イントロダクション
– 星周氷
– 銀河系外YSO研究の意義
2. あかり衛星を用いたマゼラン雲内のYSOの赤外線観測
   – 分光サーベイによるYSO探査
   – 近赤外スペクトルに基づく星周氷の研究
   – マゼラン雲と天の川銀河におけるYSO星周物質の性質の違い
3. まとめと今後の展望

Chemistry in Star-forming Regions



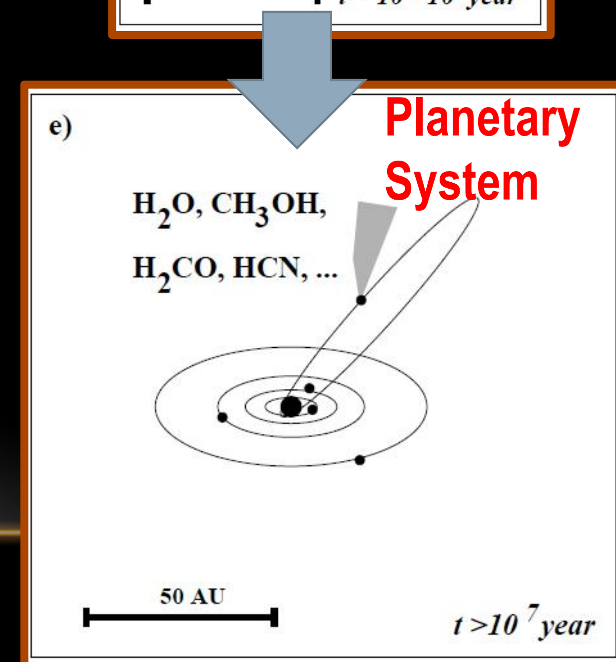


Fig.1 Star formation and chemical evolution of circumstellar materials [van Dishoeck and Blake, 1998]

Snow in the Earth's Cloud

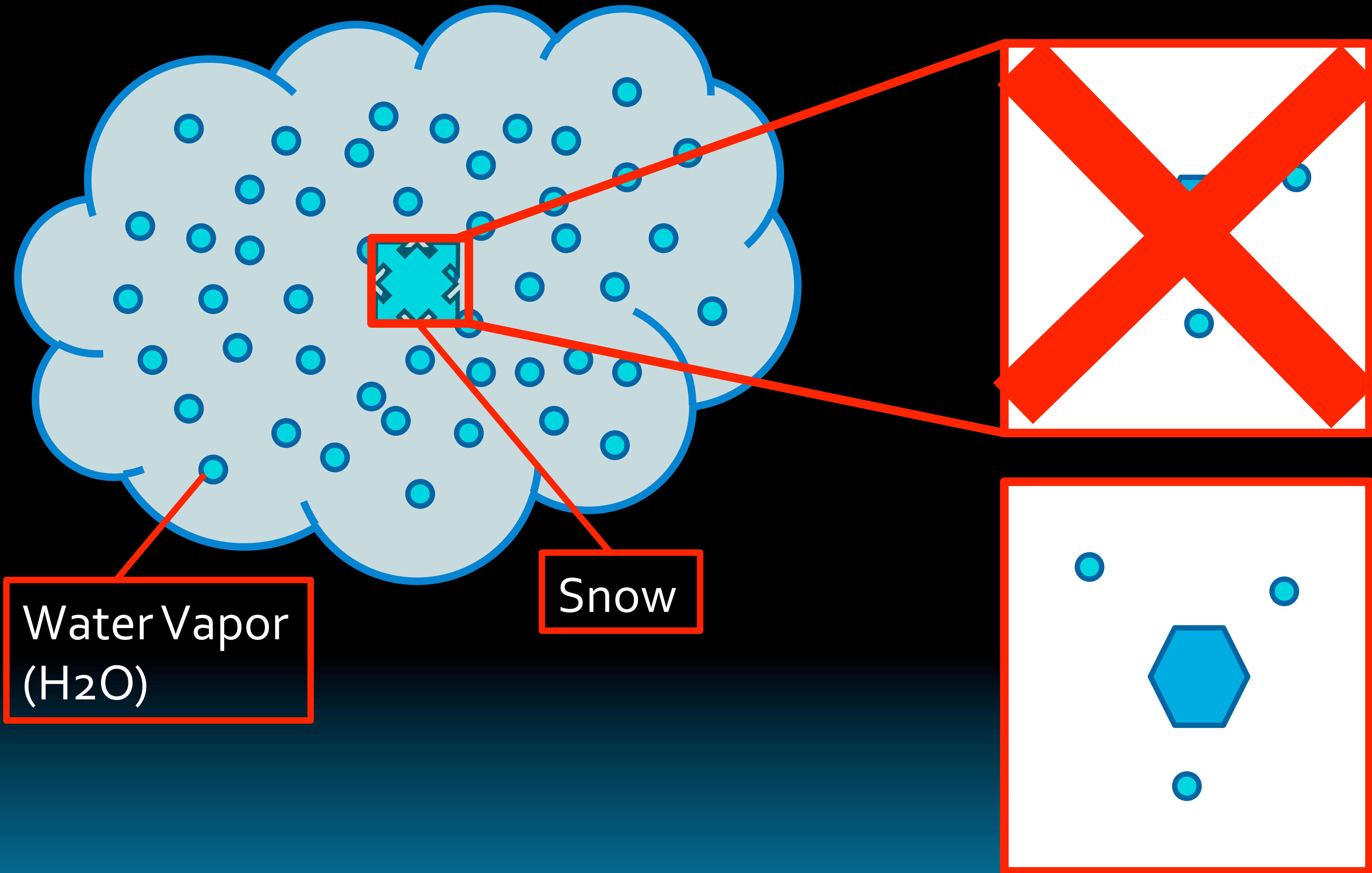
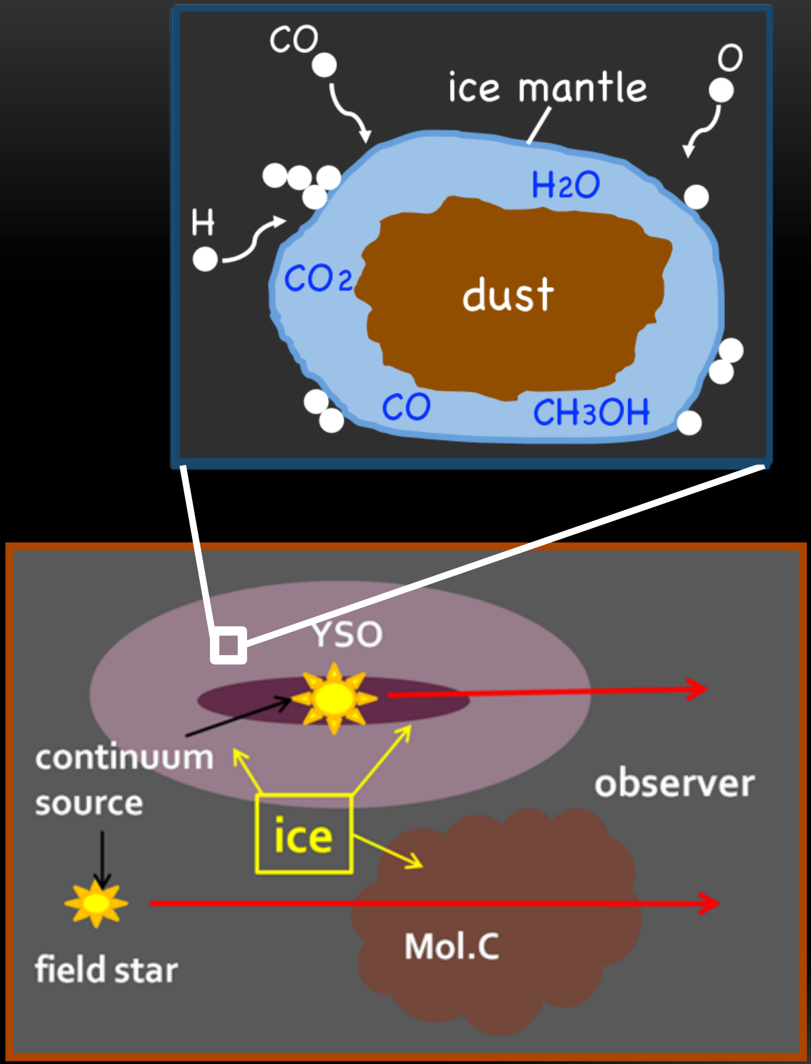


Fig.2 Formation of snow

Ices around Embedded Young Stellar Objects



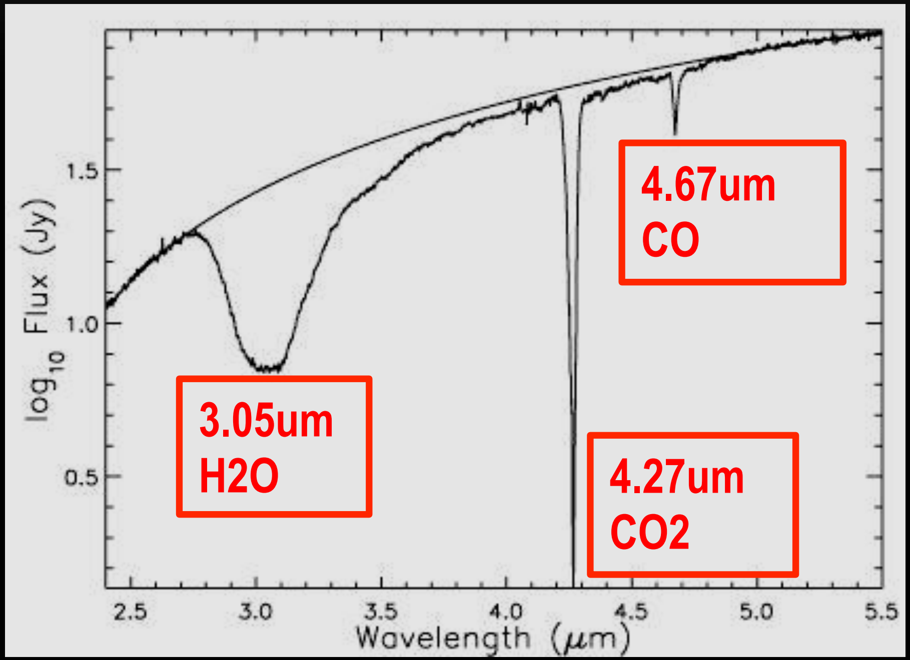


Fig.4 ISO spectrum of an embedded YSO [Gibb et al. 2004]

Fig.3 Formation of ices in the dense region of Mol. C [Boogert & Ehrenfreund, 2004]

What we know and don't know about cosmic ices

Table.1 Abundances of ices toward various objects

Species	High-mass YSO [%]	Low-mass YSO [%]	Comets [%]
H_2O (water)	…	…	…
CO_2 (carbon dioxide)	12--22	22--35	2-24
CO (carbon monoxide)	7--19	20--61	6-30
CH_4 (methane)	<2--4	<4--7	0.2-1.2
CH_3OH (methanol)	<5--16	<5--12	～2
NH_3 (ammonia)	--	<4--6	～1.5

Ref. Gibb+ 2000, Fraser+ 2002, Keane+ 2002, Oberg+ 2011,
Ootsubo+ 2012 (submitted)

istry
es
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Extragalactic YSOs

- How do characteristics of galaxies affect the properties of circumstellar materials of YSOs?

Metallicity is the key parameter of galaxies

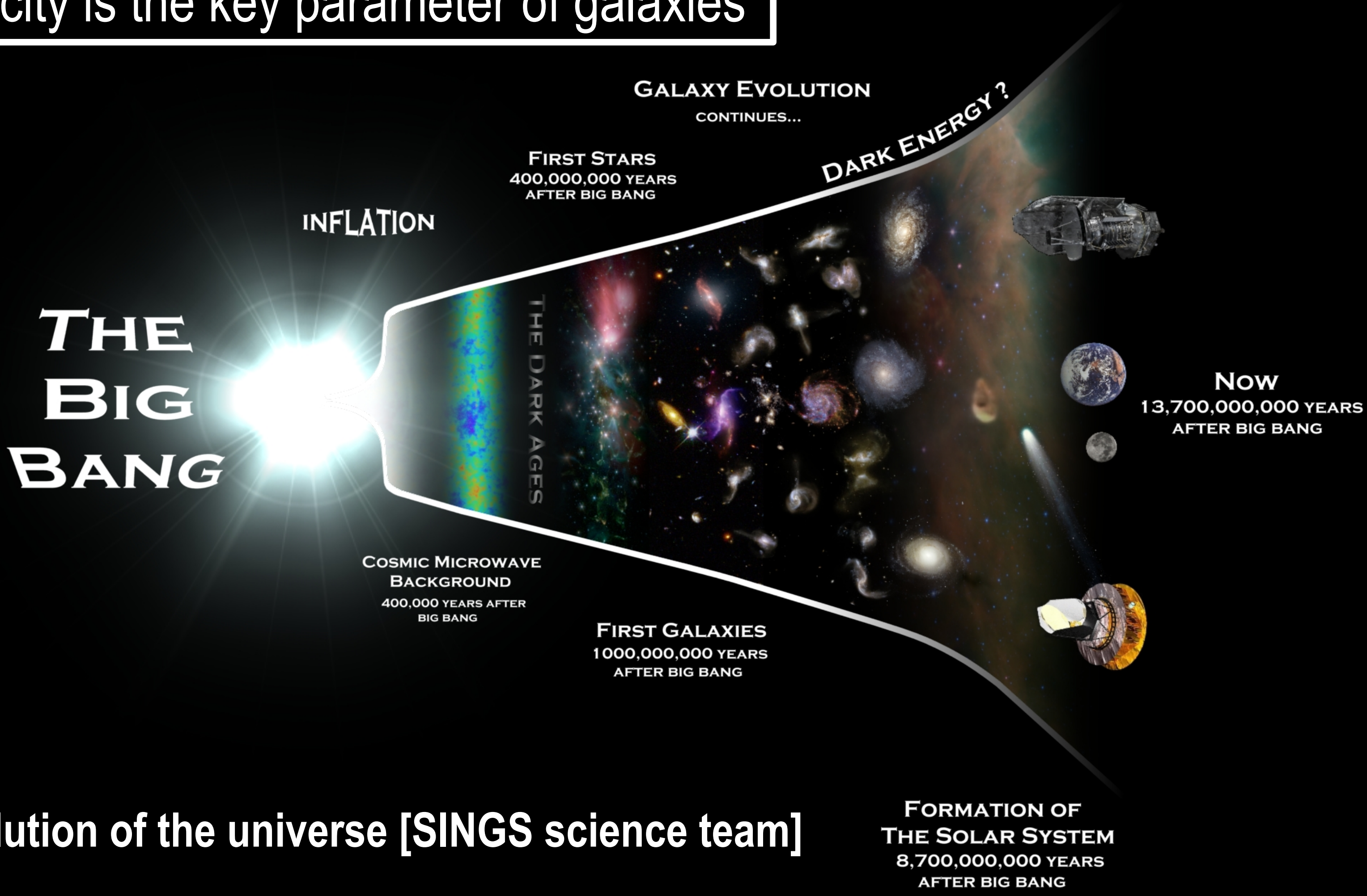


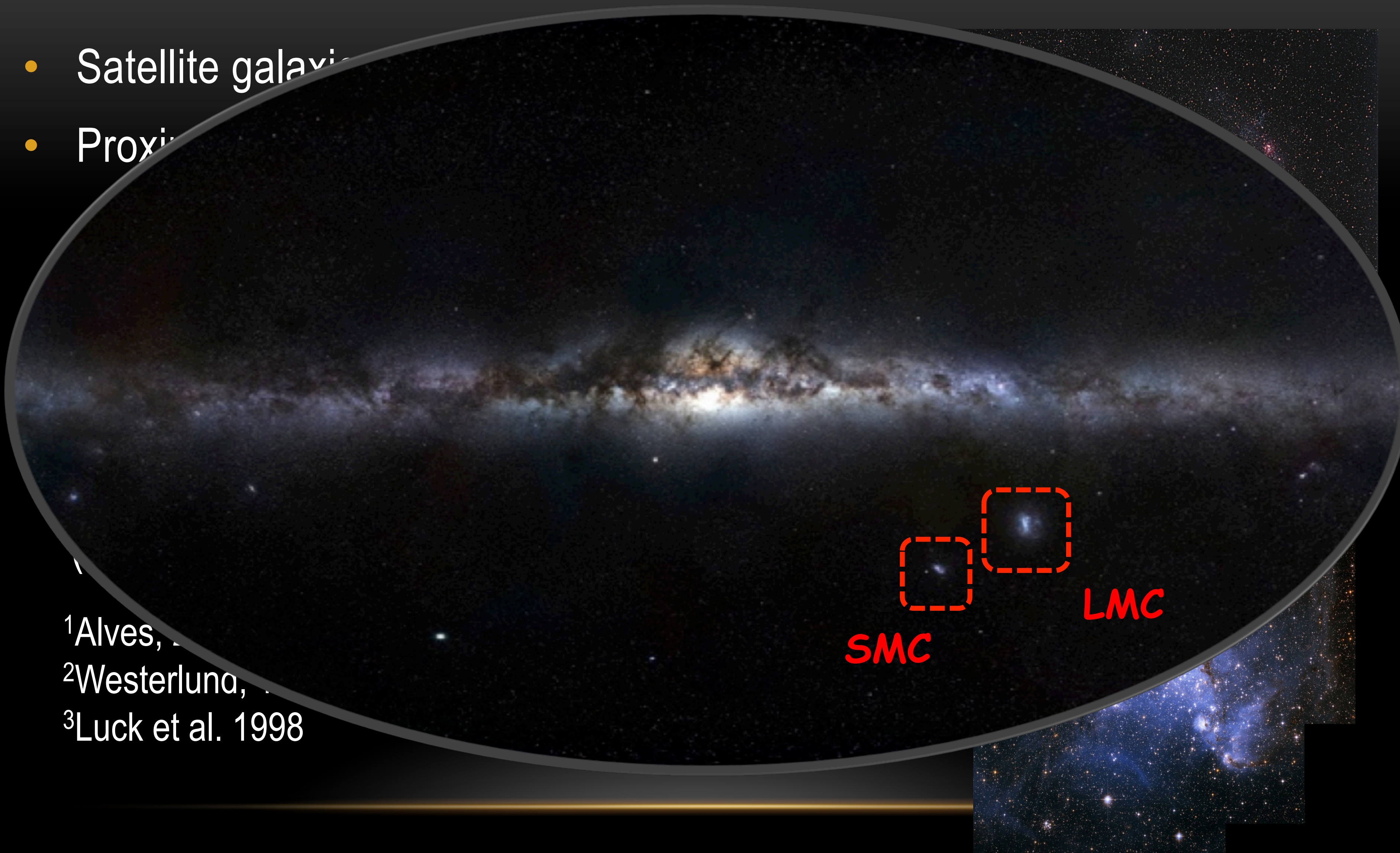
Fig.5 Evolution of the universe [SINGS science team]

The Large and Small Magellanic Clouds

- Satellite galaxi
- Proxi

(

[1]Alves, 2
[2]Westerlund, 1
[3]Luck et al. 1998



[4]E. Slawik (LMC), A. Nota/ESA, STScI (SMC)

Fig.6 Optical images of the LMC and SMC[4]

This Study

- Aim to investigate the effect of galactic environment on the properties of circumstellar materials around YSOs

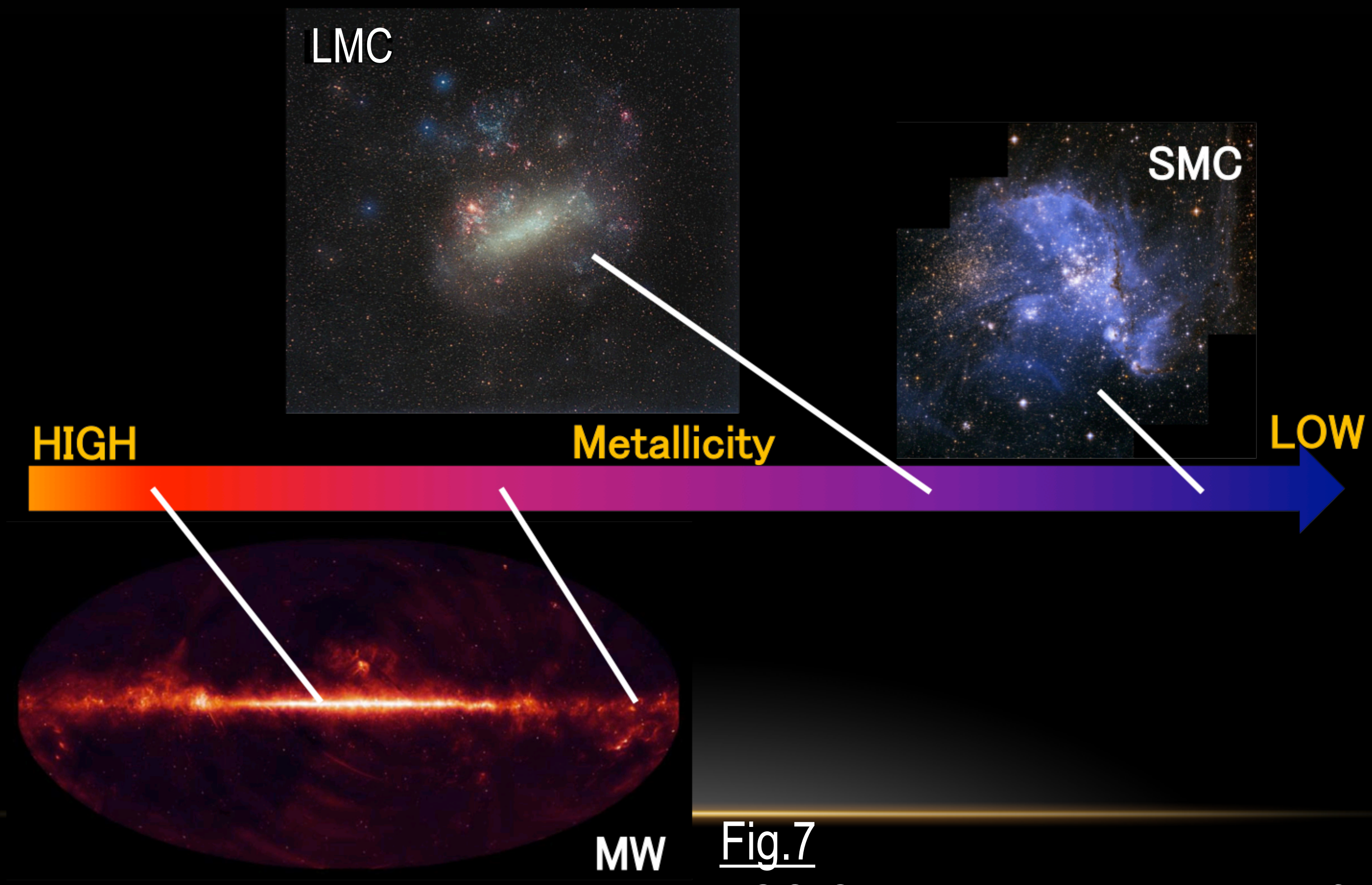
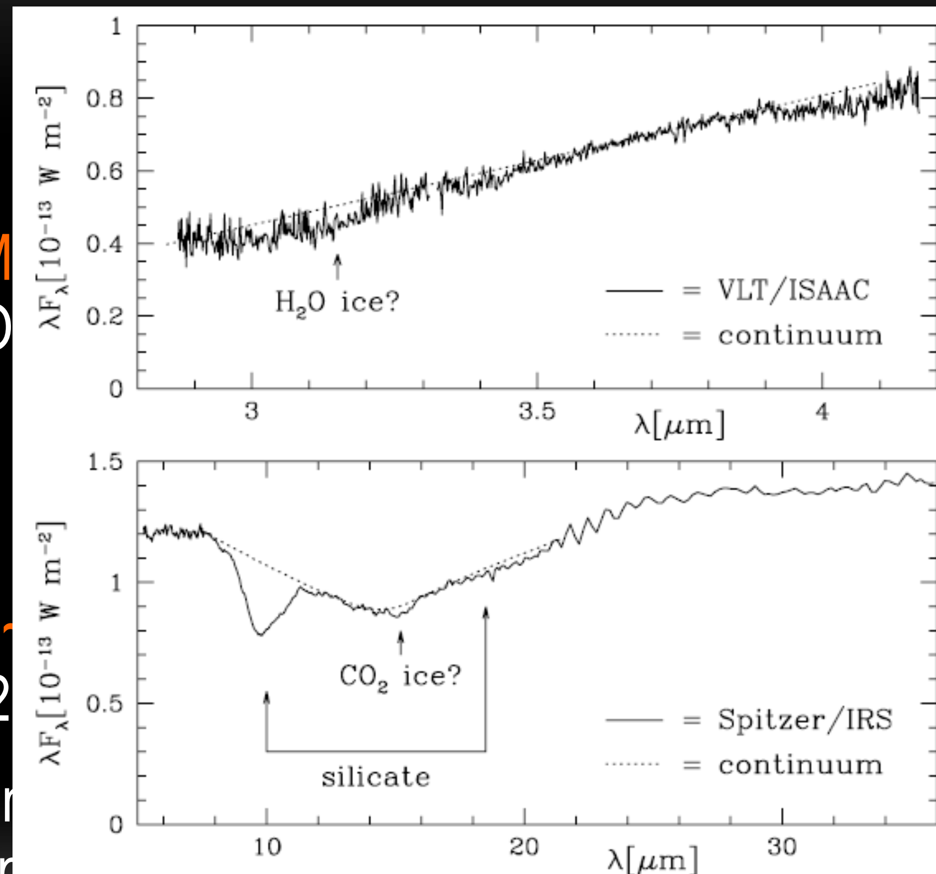


Fig.7
YSO Chemistry as a Function of Metallicity

History of Extragalactic YSO Study (on ice)

- 2005, van Loon et al.
  - — First spectroscopic detection of ices toward an extragalactic YSO
- 2008, Shimonishi et al.
  - — Discovery of 7 YSOs in the LM
    systematic comparison of the CO
- 2009-2012
  - — NIR follow-up observations of
    with AKARI (Shimonishi+ 2010, 2
  - — Ground-based MIR observatio
    Gemini/T-ReCS (Shimonishi+ in prep., Chapter 6)
  - — MIR observations of ~40 LMC's YSOs and 5 SMC's YSOs with Spitzer and ISAAC/VLT (Seale+ 2009,2010, Oliveira+ 2009,2010)



Difficulty in the Photometric Identification of YSOs

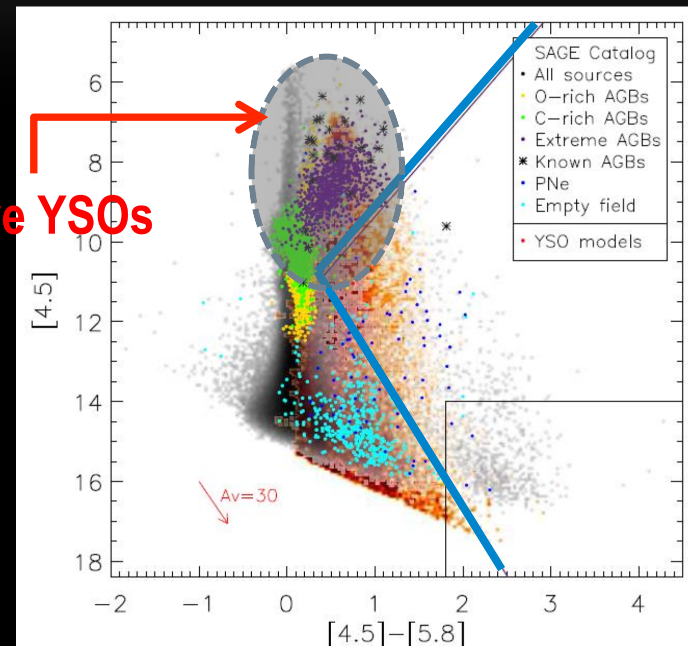
- Need massive YSO samples for spectroscopic study of ices
- Traditionally, YSOs are classified based on Color-Magnitude (-Color) Diagrams

However,

Embedded massive YSOs are difficult to find only by the photometric criteria

Because YSOs have similar infrared color and brightness to those of dusty evolved stars

Massive YSOs



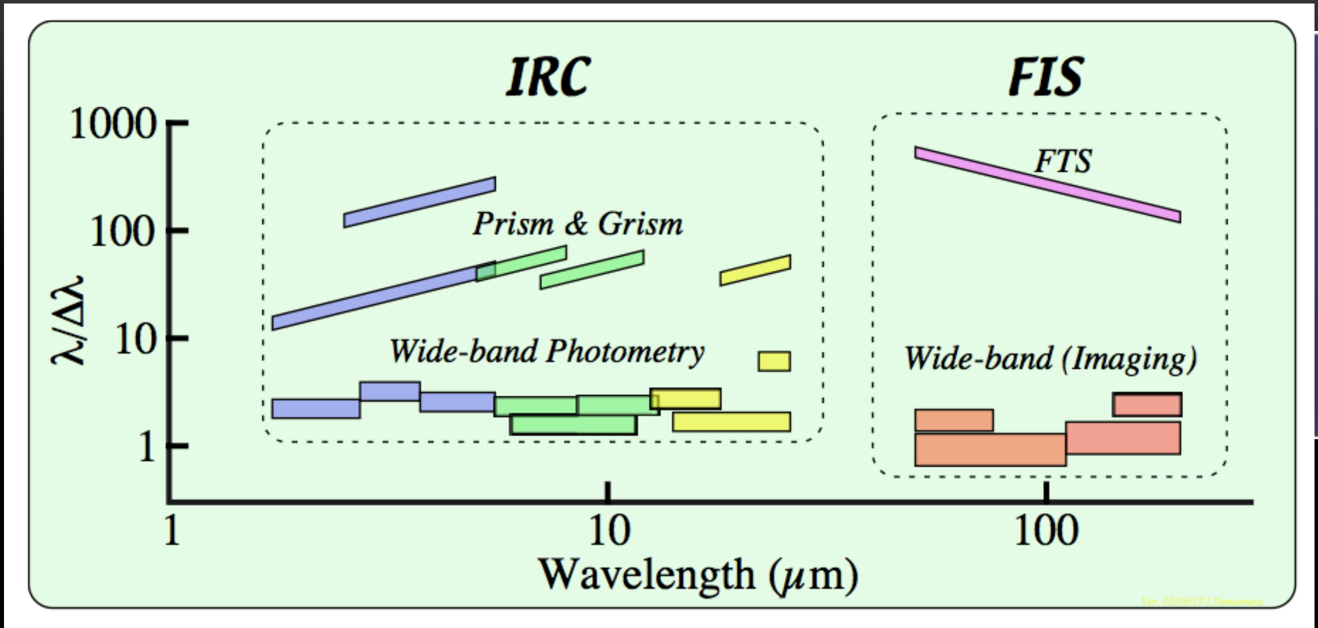
● : YSOs (model)

●●● : Dusty evolved stars

● : Others

Fig.8 Selection of YSOs based on the Color-Magnitude diagram (Whitney et al. 2008)

Infrared Satellite *AKARI*[1]



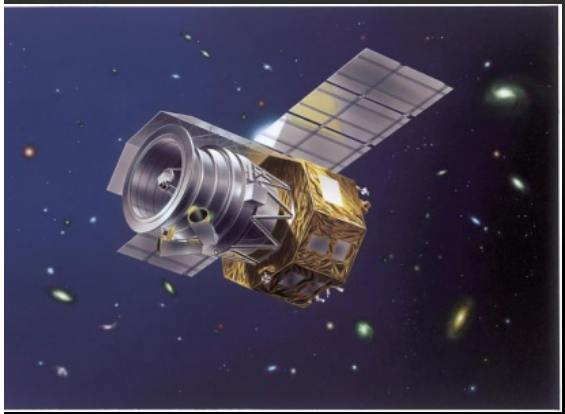


Fig.9 *AKARI* in space

Two scientific instruments:

- InfraRed Camera[2] (IRC) … 2 – 26 μm
- Far-Infrared Surveyor[3] (FIS) … 50 -- 180μm

[1]Murakami et al. 2007 [2]Onaka et al. 2007 [3]Kawada et al. 2007

Infrared Satellite *AKARI*[1]

- Infrared Camera[2] (IRC)
  - 2.0—5 μm, R~20, 80, 100
  - Detection limit: ~0.1, 1mJy
  - Spatial resl.: ~6" (~1.5pc at LMC)

IRC/AKARI covers absorption features of major ice species

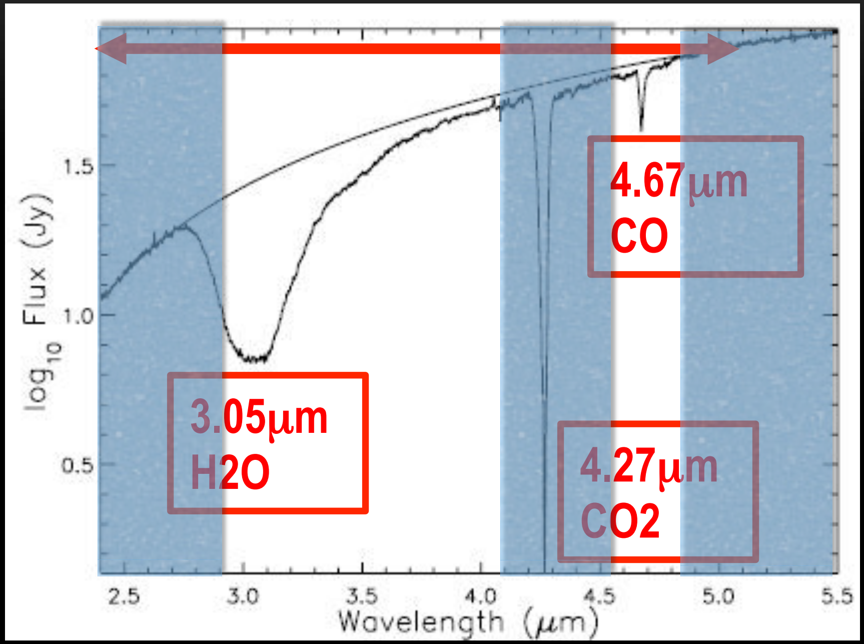


Fig.10 ISO spectrum and AKARI/IRC wavelength covarage [from Gibb et al. 2004]

[1]Murakami et al. 2007 [2]Onaka et al. 2007

AKARI LMC Spectroscopic Survey

AKARI Large-area Survey of the Large Magellanic Cloud (LSLMC, PI. T. Onaka)

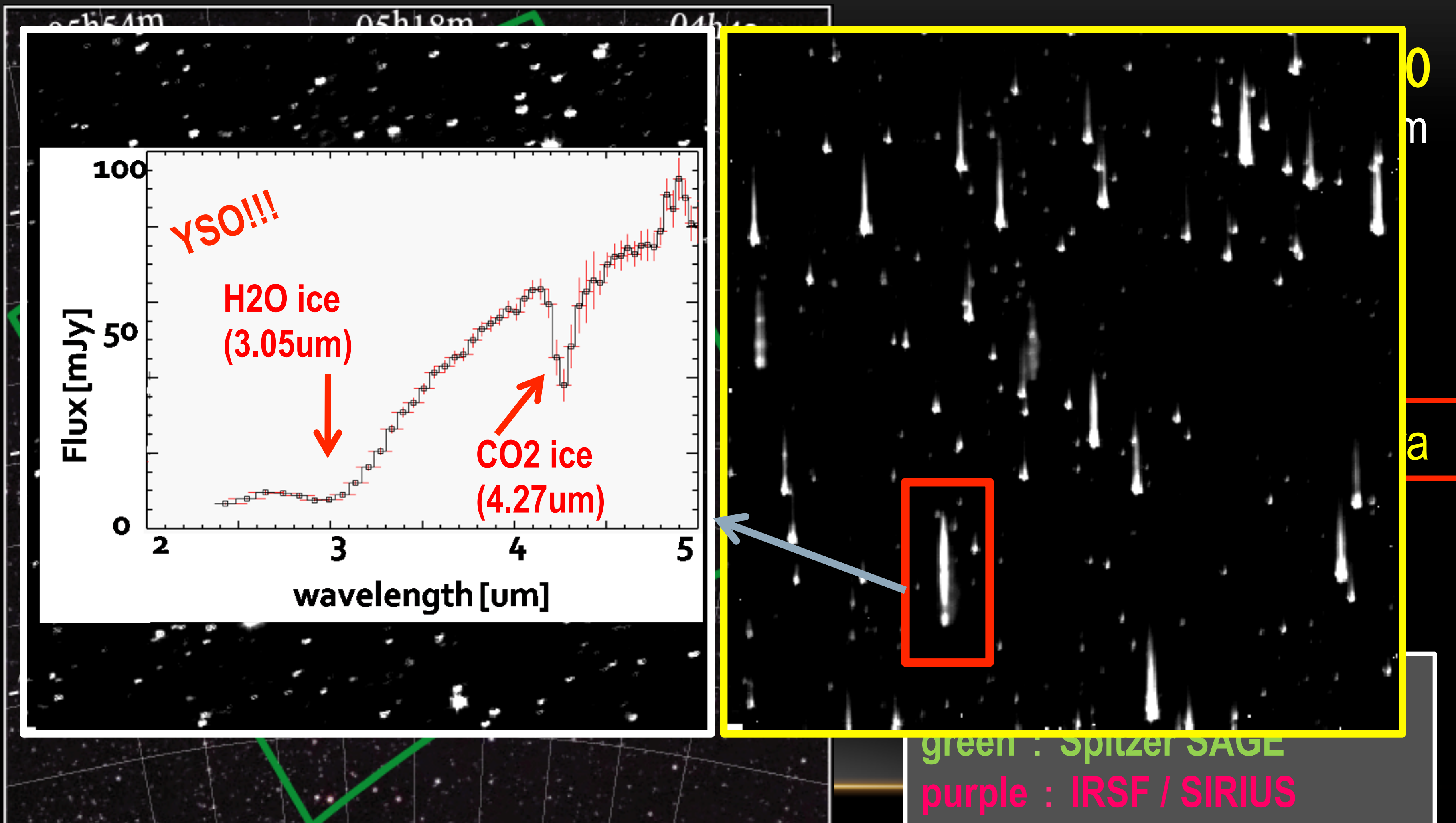
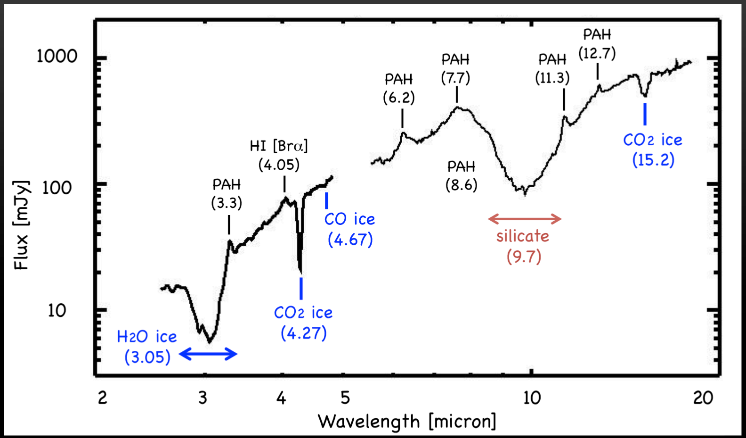


Fig. 11 *AKARI* LMC spectroscopic survey area

How many YSOs (with ice detection) in the MCs?

Number of ISO-SWS
high-mass
Galactic YSO samples = ~15



Instrument	Cloud	Number	Ice band	Reference
AKARI/IRC	LMC	20	H_2O, CO_2, CO, CH_3OH, (XCN)	Shimonishi et al. 2008, 2010, Thesis
	SMC	2	H_2O, CO_2	Shimonishi, Thesis
Spitzer/IRS	LMC	41	CO_2, Silicate	Seale et al. 2010, Oliveira et al. 2009
	SMC	4	CO_2, Silicate	Oliveira et al. 2011
VLT/ISAAC	LMC	4	H_2O, (CH_3OH), CO	van Loon et al. 2005, Oliveira et al. 2011
	SMC	4	H_2O	Oliveira et al. 2011
Gemini/TReCS	LMC	1 (3)*	Silicate	Shimonihi, Thesis
	SMC	(1)*	Silicate	Shimonishi, Thesis

*Only narrow band photometry

Spectra Obtained by the LSLMC Survey

In total, ~2000 spectra !

- YSOs
- Compact HII regions
- C- / O-rich AGB stars
- Super-giants
- Galaxy, PNe, Wolf-Rayet, post-AGB
- unknown

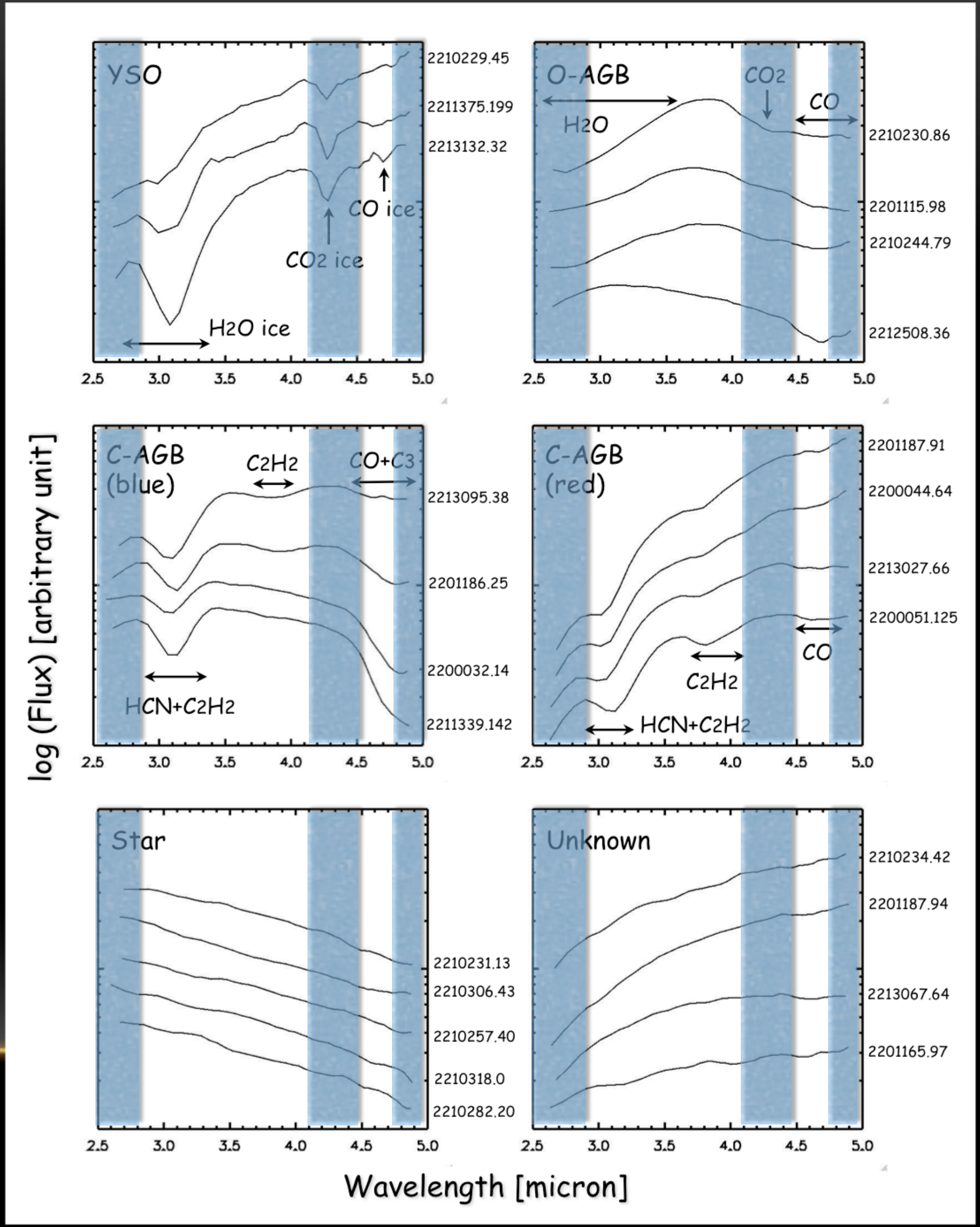


Fig. 12 Examples of extracted spectra

Construction of NIR Spectroscopic Catalog

- Catalog containing ~2000 spectra and photometric data
- Technical discussions on data reduction of slit-less spectroscopic data
- Source classification based on NIR spectra

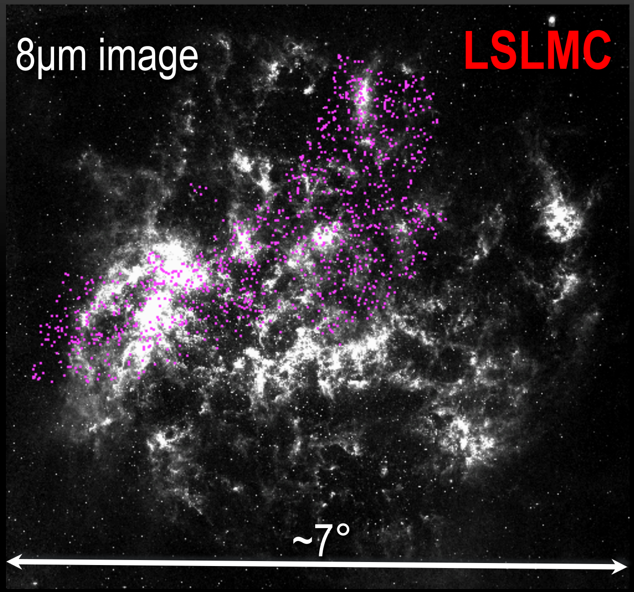


Fig.12 Distribution of LSLMC sources

Shimonishi et al. 2012 (submitted to AJ)
"AKARI Infrared Camera Survey of the Large Magellanic Cloud. II. The Near-Infrared Spectroscopic Catalog"

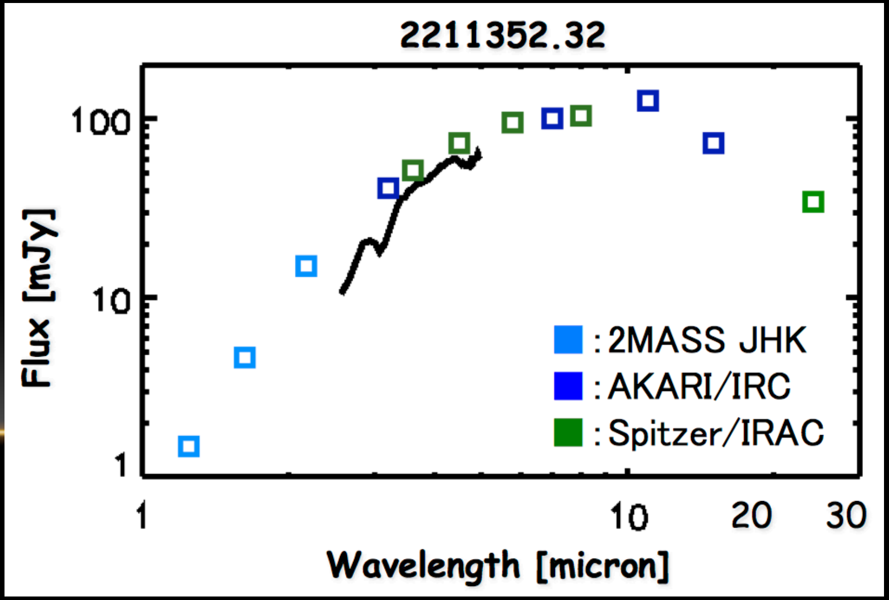


Fig.13 Example of a spectrum in the catalog

Observations of MC's YSOs with AKARI

"Ices around Extragalactic YSOs" (IEYSO, PI. T. Shimonishi)
"Near-infrared Spectroscopic Observations of Red Objects in the LMC" (LMCNG, PI. T. Onaka)
+ Director's Time observations

Sample
20 Class I YSOs
$L = 5 - 370 \times 10^4\ L_\odot$
$M = 10 - 40\ M_\odot$

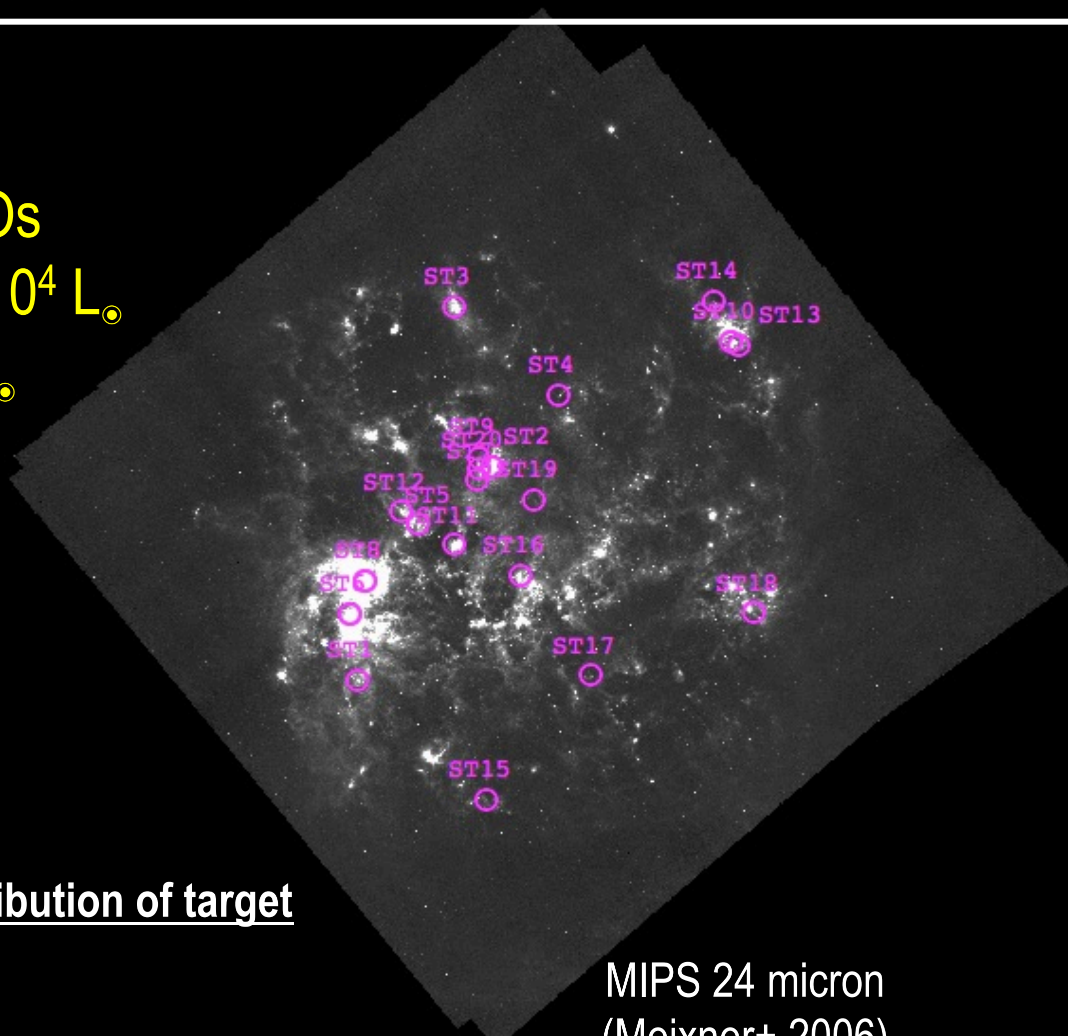
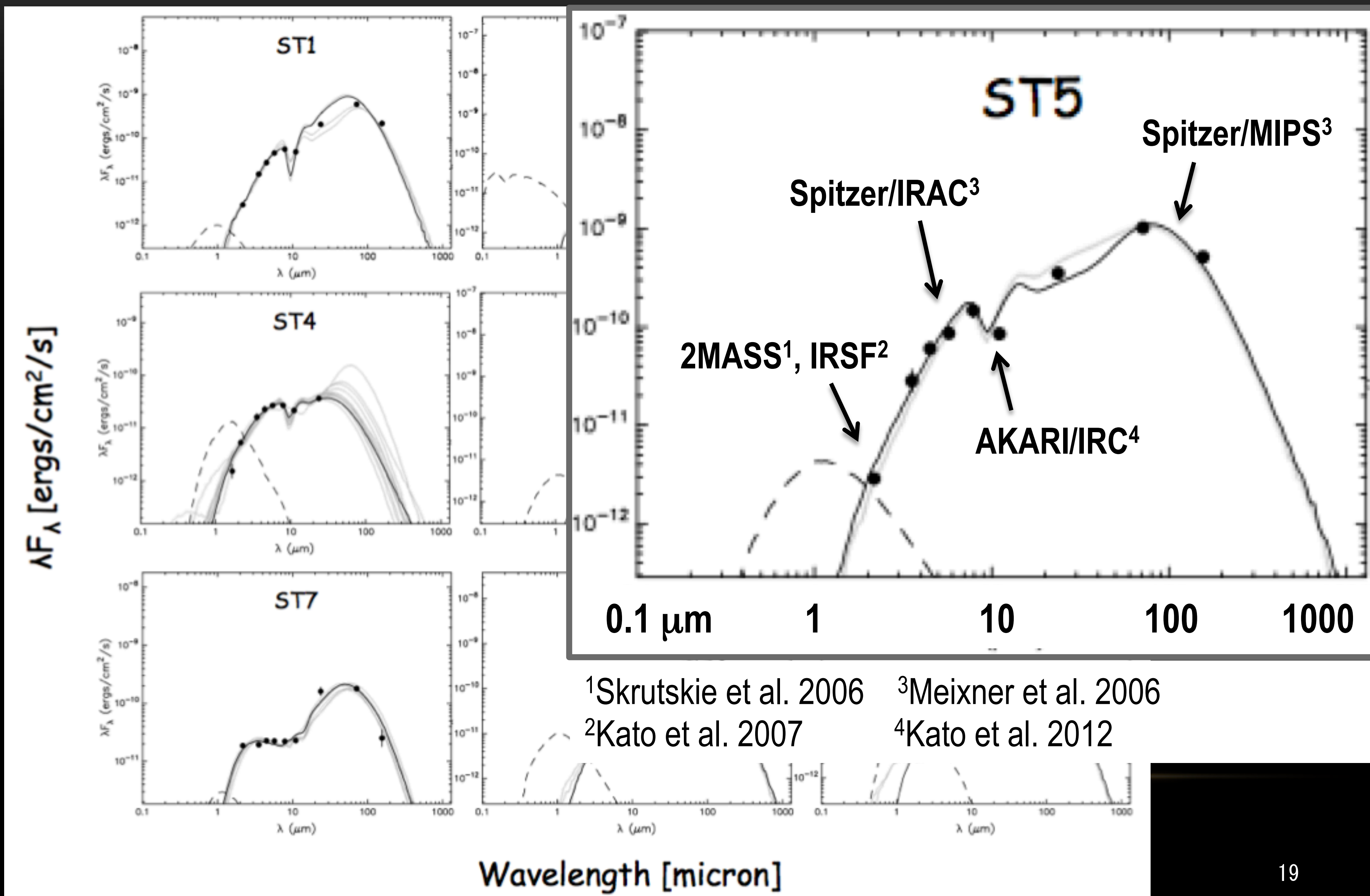


Fig. 14 Spatial distribution of target YSOs in the LMC

MIPS 24 micron
(Meixner+ 2006)

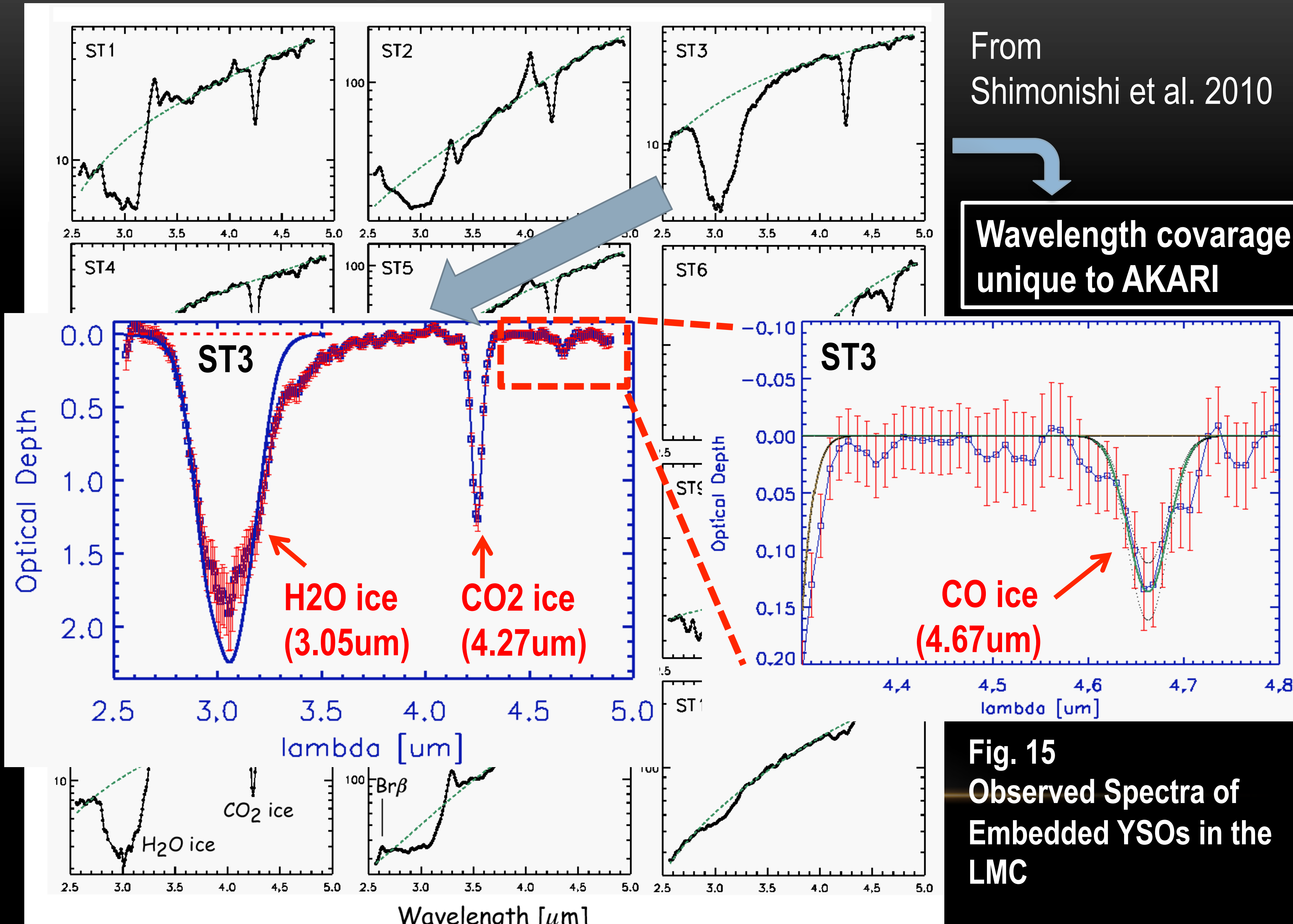
SED Fit

- YSO model by Robitaille et al. 2006 is used to estimate the luminosity



[1]Skrutskie et al. 2006
[2]Kato et al. 2007
[3]Meixner et al. 2006
[4]Kato et al. 2012

AKARI NIR Spectra of Embedded YSOs in the LMC



From
Shimonishi et al. 2010

Wavelength covarage unique to AKARI

Fig. 15
Observed Spectra of Embedded YSOs in the LMC

Ice Detections toward LMC's YSOs

Number	H_2O	CO_2	CO	CH_3OH	$^{13}CO_2$	XCN
ST1	√	√	√	—	—	—
ST2	√	√	—	√	?	—
ST3	√	√	√	—	—	—
ST4	√	√	√	—	—	—
ST5	√	√	√	√	—	—
ST6	—	√	√	—	—	?
ST7	√	√	√	—	√	?
ST8	√	√	√	—	√	—
ST9	?	√	√	—	?	—
ST10	√	√	√	—	—	?
ST11	√	√	—	?	—	—
ST12	√	√	—	?	—	—
ST13	√	√	?	?	—	—
ST14	√	√	√	—	—	—
ST15	√	√	?	—	—	—
ST16	√	√	?	—	—	—
ST17	√	√	√	—	—	—
ST18	√	√	—	—	—	—
ST19	√	√	?	—	—	—
ST20	?	√	—	—	—	—

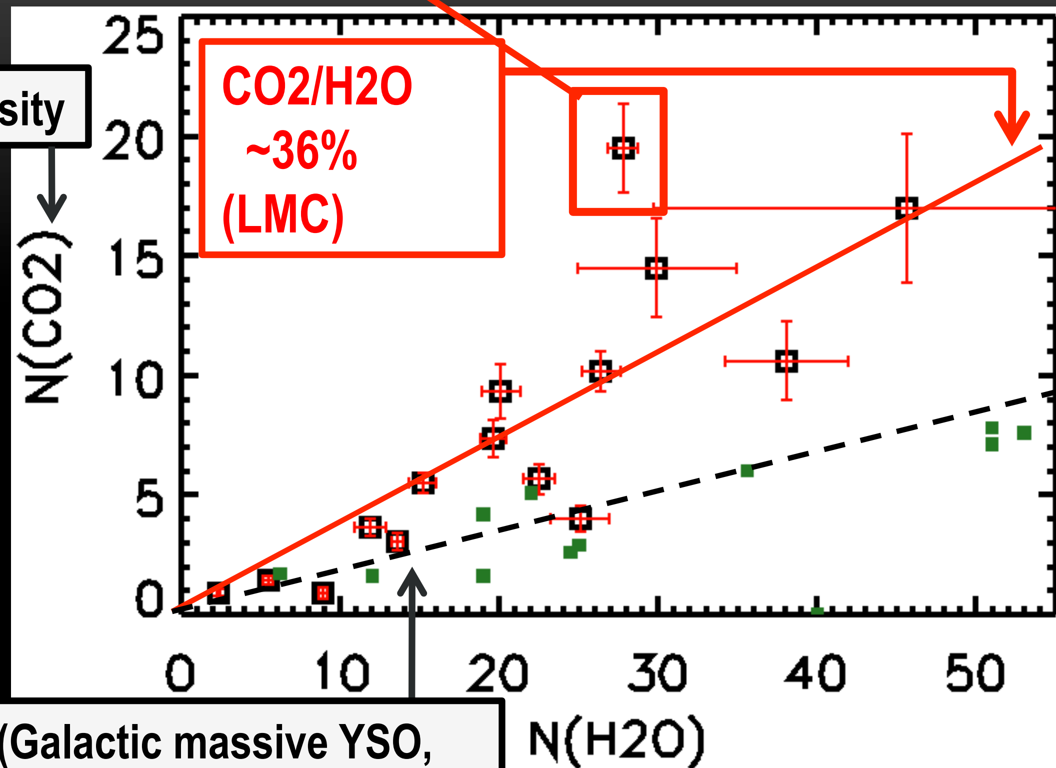
High CO_2 ice Abund … e LMC

CO2/H2O ~ 70% !!!

- ☐ : LMC's YSO[1]
- ■ : MW's YSO[2]

1. Shimonishi+ 2010
2. Gibb+ 2004

Ice Column Density



17% (Galactic massive YSO, Gerakines et al. 1999)

*10^{17} [molecule * cm^{-2}]

Fig.16 H2O ice vs. CO2 ice column density

LMC's YSOs have chemically different nature from Milky Way's YSOs.

Formation Mechanism of CO_2 ice

Experiment

■ High activation barrier in the CO_2 ice formation reaction:

$CO + O \rightarrow CO_2$?

■ Need **UV radiation field** (e.g. Watanabe et al. 2007)

■Recently reproduced by experiment **(e.g., Oba+ 2010)**

Observation

■ Abundant detection of CO_2 ice in Mol.C (Whittet et al.1998)

↓

No need for UV photons?

Theory

■ "Diffusive Grain Surface Chemistry"

$CO + OH \rightarrow CO_2 + H$?

$O + HCO \rightarrow CO_2 + H$?

↓

Dust temperature

The model suggests high dust temperature produce sufficient CO_2 ice (Ruffle & Herbst, 2001)

Others

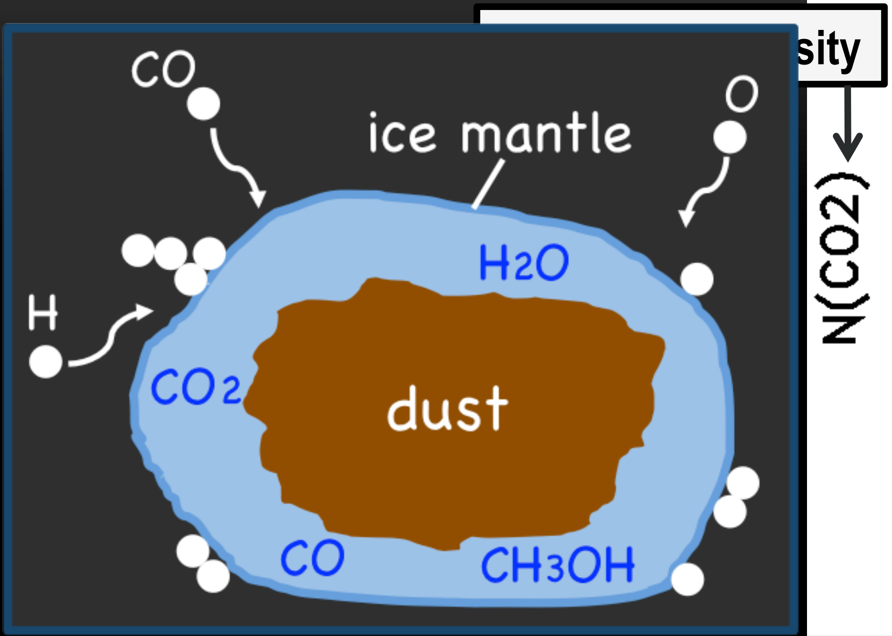
- **Elemental abundance** of the galaxy (e.g. C/O ratio, ref. Das+ 2010)
- **Cosmic ray density** (CR-induced UV)

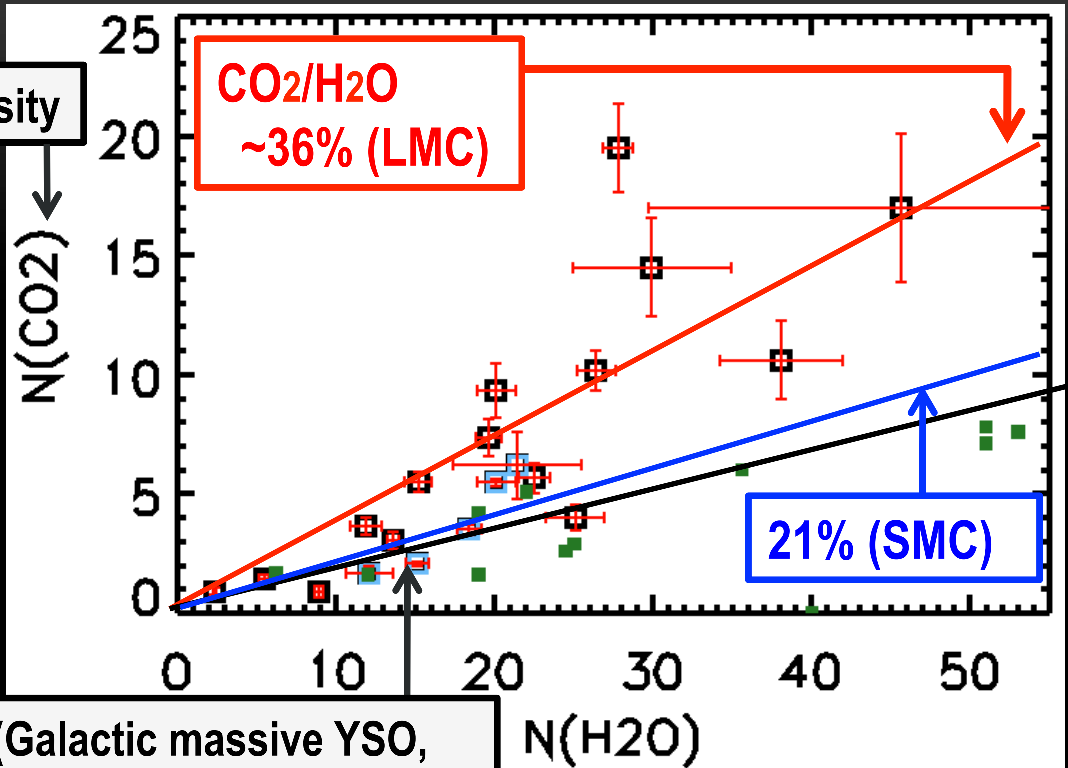
– UV photon inside a dense cloud is induced by cosmic ray (e.g. Prasad & Tarafdar, 1983)

Environment of the LMC

- C/O ratio in the LMC
  — is lower or nearly same with our Galaxy (MW : LMC = 1 : 0.5)
  (Dufour+ 1982, Andrievsky+ 2001, Rollenston+ 2002)
- CR density in the LMC
  — is 25~50% smaller than that of typical Galactic value
  (Abdo+ 2009, 2010 based on gamma-ray observations by FERMI)
- UV radiation field in the LMC
  — is 10—100 times stronger than typical Galactic value
  (Israel & de Graauw, 1986, Tumlinson+ 2002)
- Dust temperature in the LMC
  — is higher than our Galaxy (e.g., MW: 15 --19K, LMC: ~25K, SMC: ~30K, Aguirre+ 2003, results for diffuse regions)

CO_2 ice in the SMC





17% (Galactic massive YSO, Gerakines et al. 1999)

$*10^{17}$ [molecule * cm^{-2}]

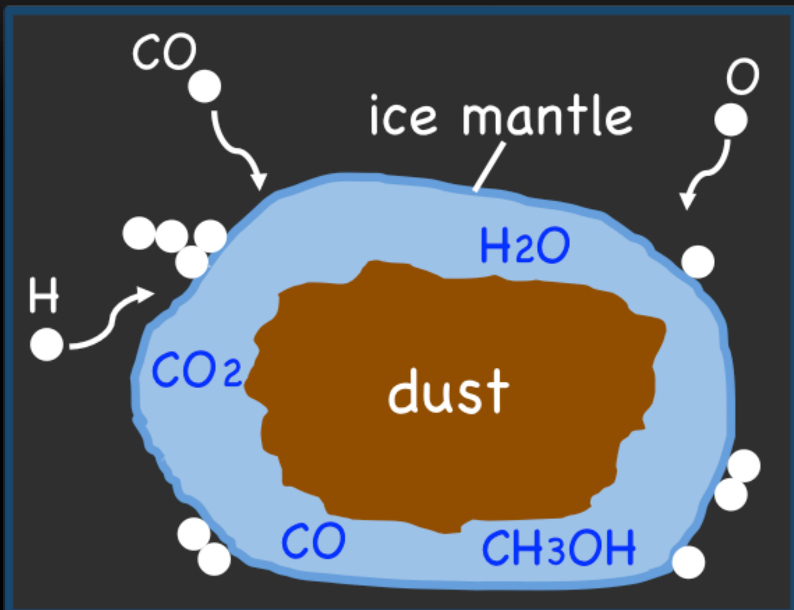
Fig.17 H_2O ice vs. CO_2 ice column density

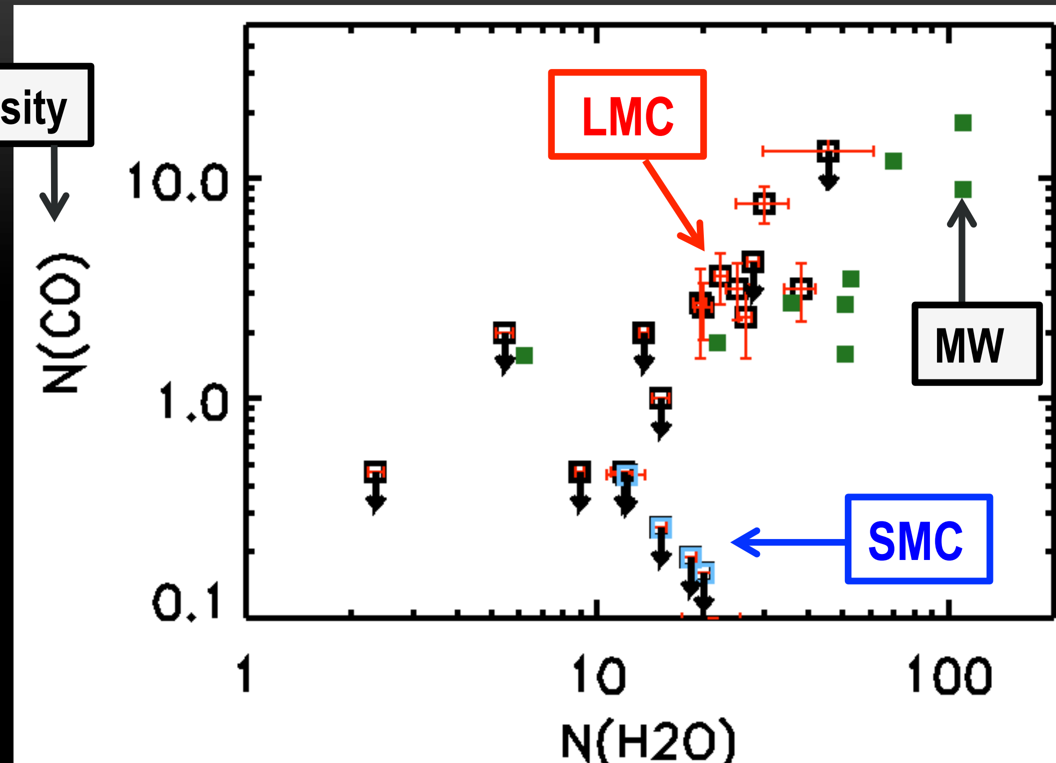
CO_2 ice abundance of SMC's YSO is intermediate between LMC and MW

→ **Dust temperature in the SMC may be too high for the efficient CO_2 production**

CO ice in the SMC

Ice Column Density





*10^{17} [molecule * cm^{-2}]

Fig.18 H2O ice vs. CO2 ice column density

No CO ice detection toward SMC's YSOs

→ **Dust temperature in the SMC may be too high for the CO ice to remain on the surface**

T-ReCS MIR Observations

- Gemini/T-ReCS observations

("Dust and Ices around Extragalactic YSO",

PI. T,Shimonishi)

  – N-band (7.7 – 13.0 micron)
  – 0.09" / pix, seeing ~0.5"-0.6"

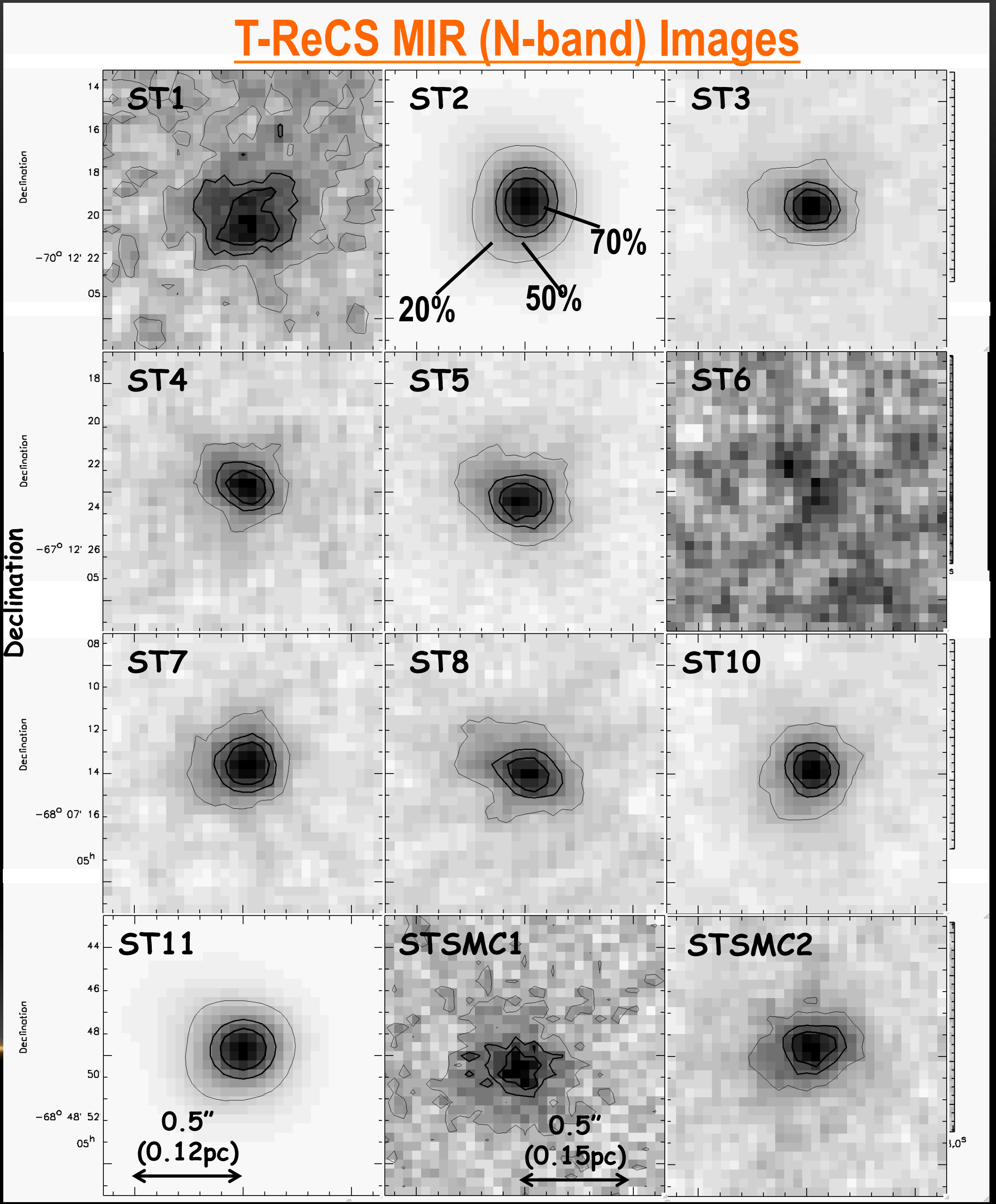
- Apertures in previous observations
  – AKARI/IRC ~ 4 – 6" … 1 – 1.5 pc[a]
  – Spitzer / IRS ~ 3.6" … 0.9 pc[a]
- Typical size of protostellar core

  ~ 0.1 pc

- Results
  – No other sources around 2.5 pc[a]
  – IR flux from very compact regions

  (FWHM ~0.5" … 0.12 pc[a])

[a]at the distance of the LMC



T-ReCS MIR Observations

- T-ReCS high resolution spectroscopy coincide with the IRS spectroscopy
- Narrow band photometric values coincide with the IRS spectra

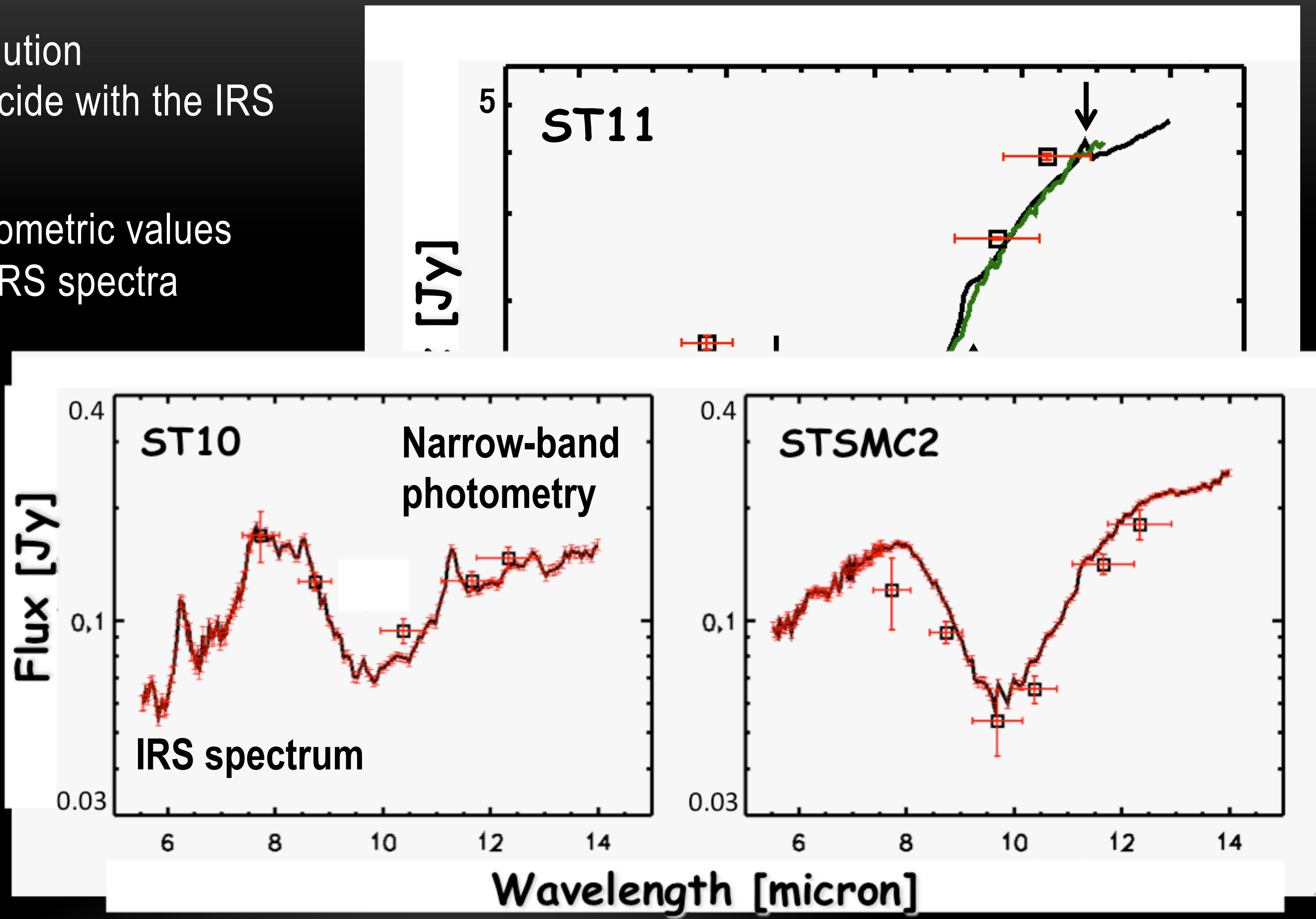


Fig.19 Ground-based high-spatial resolution spectrum vs. Spitzer IRS spectrum

At which stages are ices formed?

- Ices are already formed in molecular clouds before formation of a protostar
- Similar molecular abundance (CO_2 and CH_3OH) toward Mol.C and YSOs[1]
- Correlation between CO_2/H_2O ratio and YSO properties?[2,3]

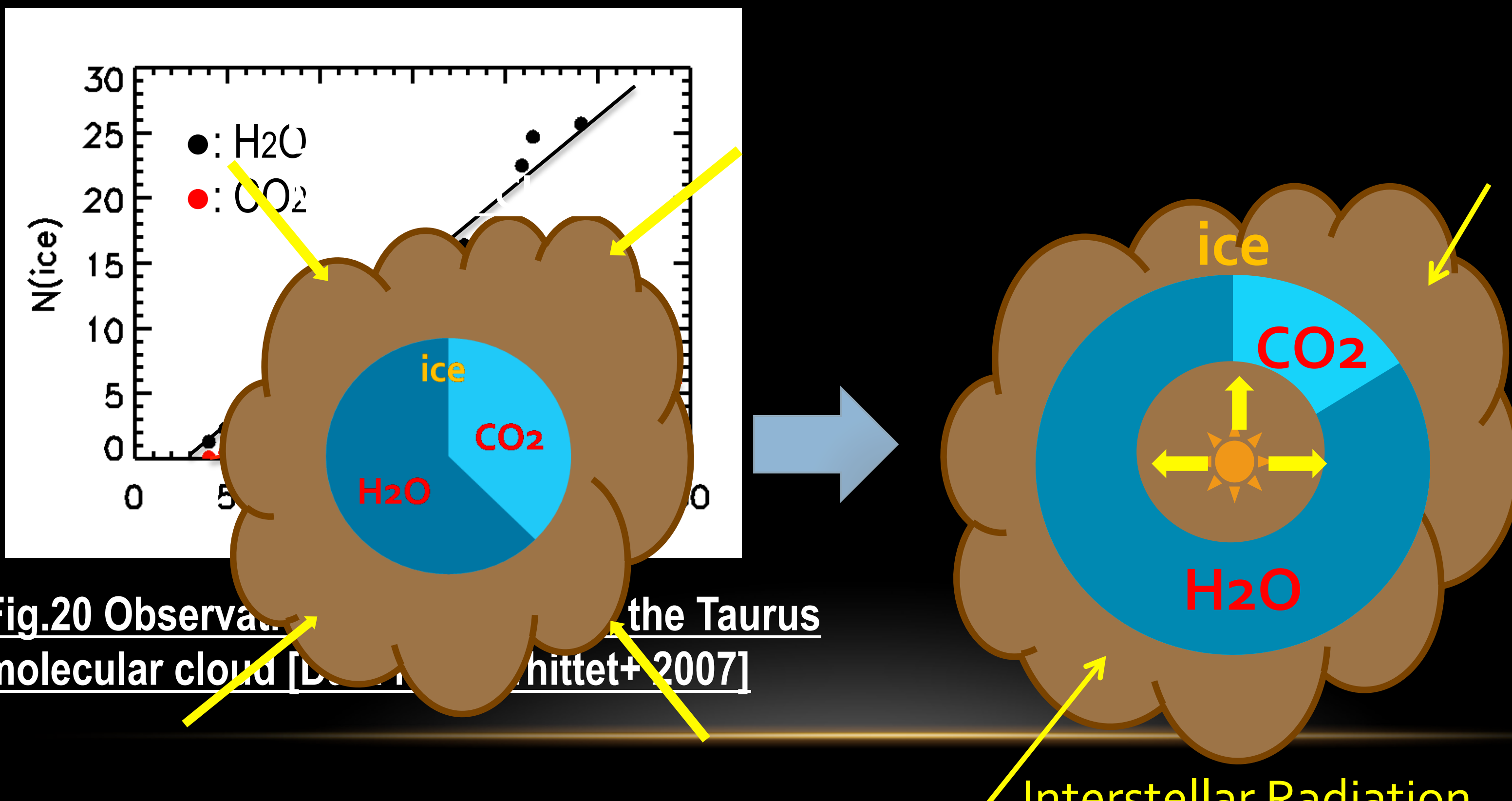


Fig.20 Observat... the Taurus molecular cloud [D... hittet+ 2007]

[1]Oberg et al. 2011, [2]Zasowski et al. 2009, [3]Cook et al. 2011

Ice Column density vs. Luminosity

● : LMC[1]

1. Shimonishi+ 2010

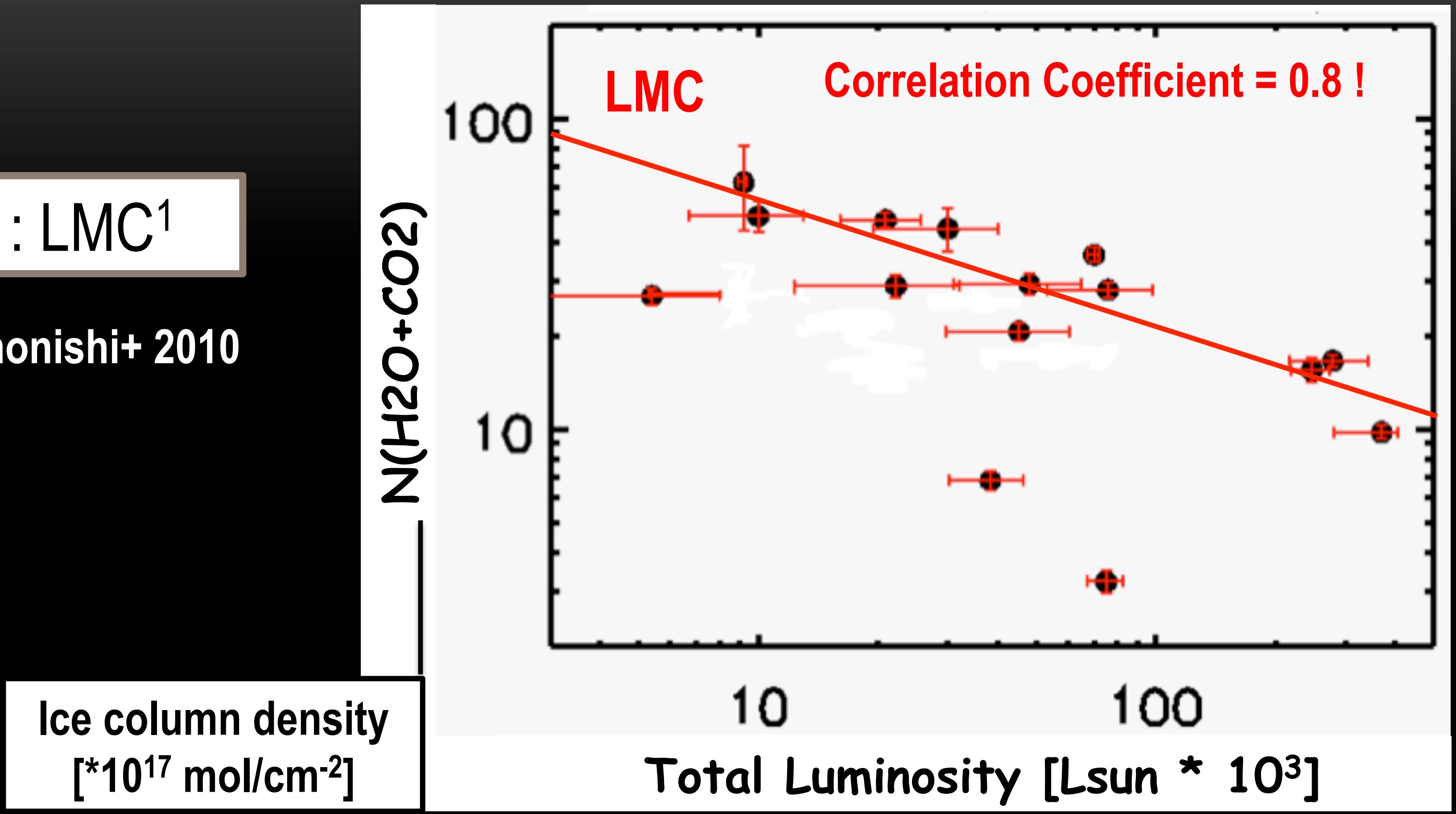


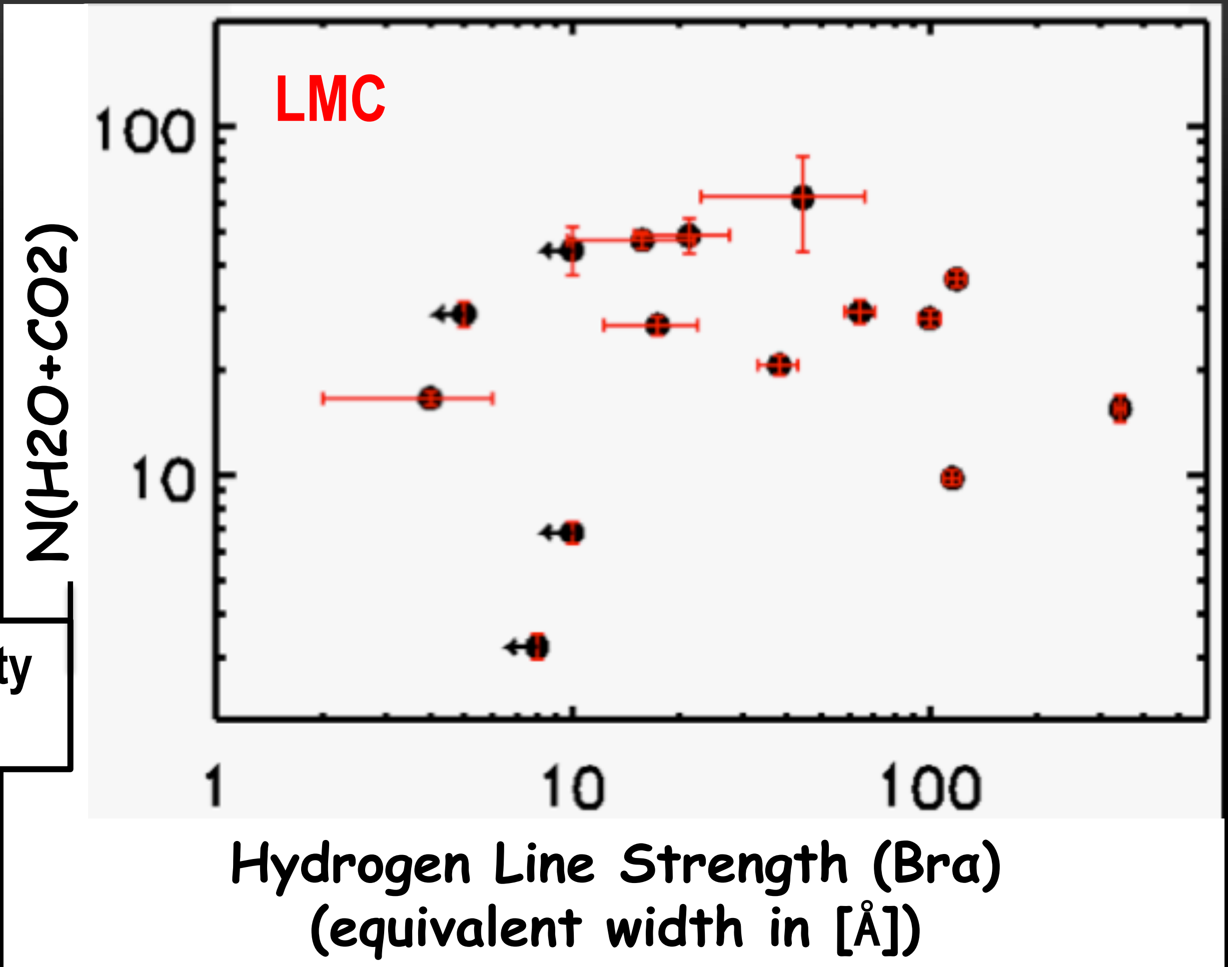
Fig.21 Ice column density vs. Luminosity of a YSO

Ice column density has a strong correlation with YSO's luminosity

Ice Column Density vs. Hydrogen Emission line

● : LMC[1]

1. Shimonishi+ 2010



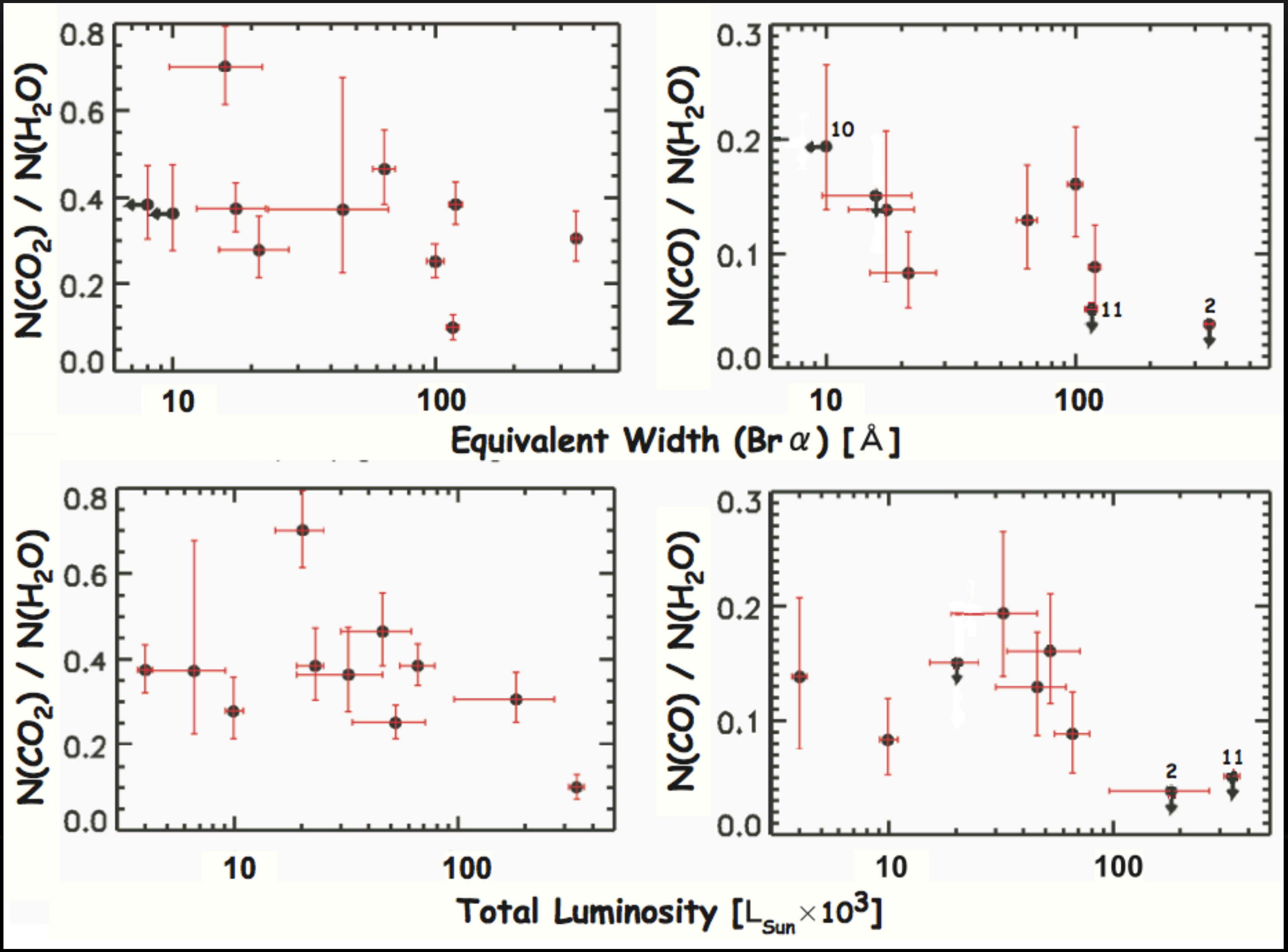
Ice column density [$*10^{17}$ mol/cm^{-2}]

Fig.22 Ice column density vs. Brα hydrogen emission line strength

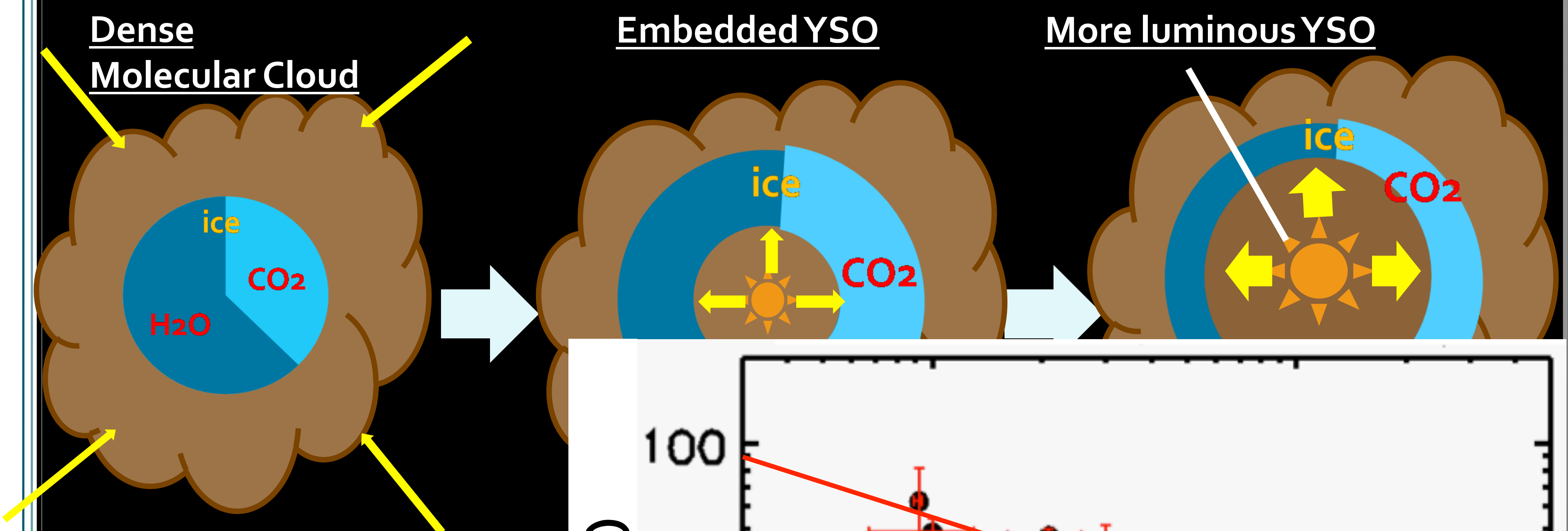
Ice column density does NOT correlate with the strength of the hydrogen recombination line (indicator of UV radiation)

Ice Abundance vs. YSO properties

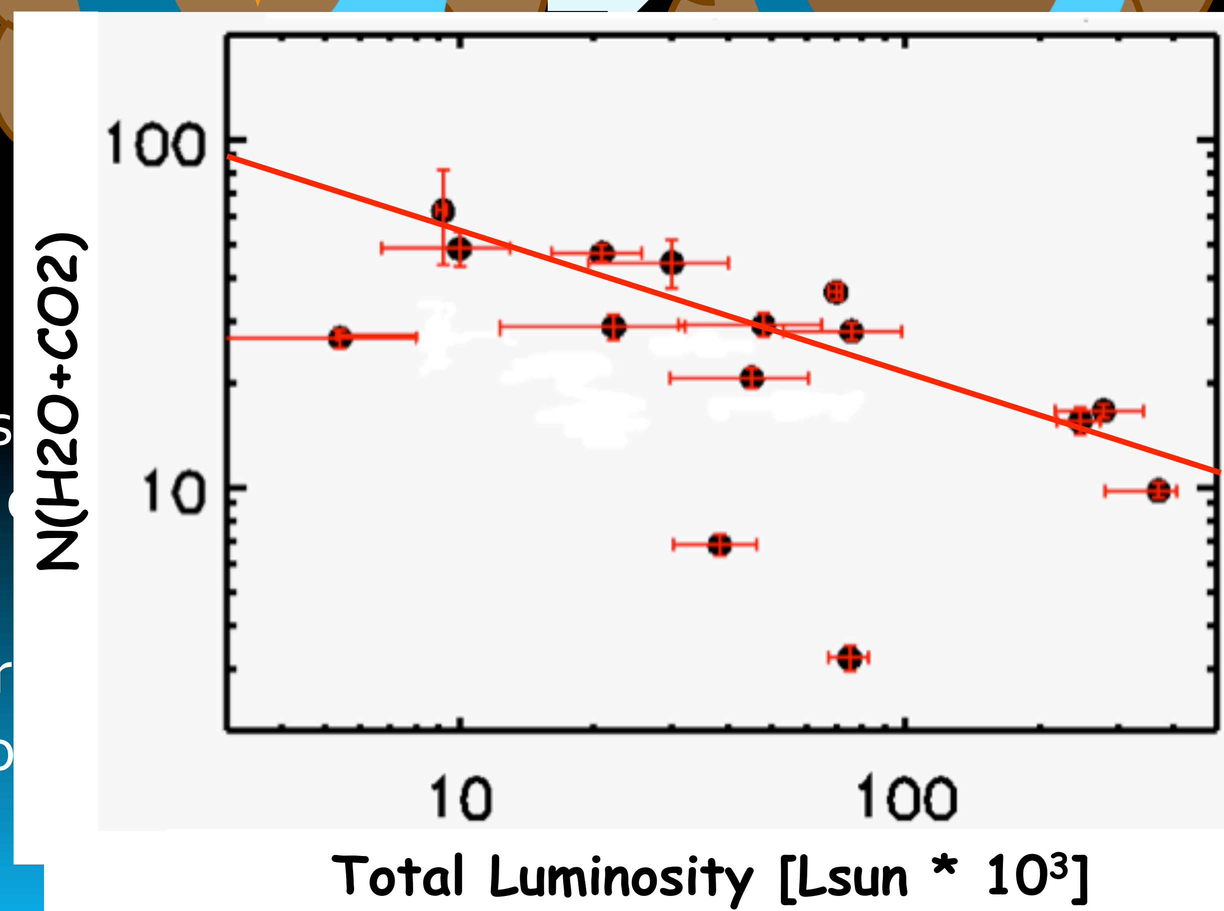
- No clear correlation between CO_2 or CO ice “abundance” and YSO’s properties



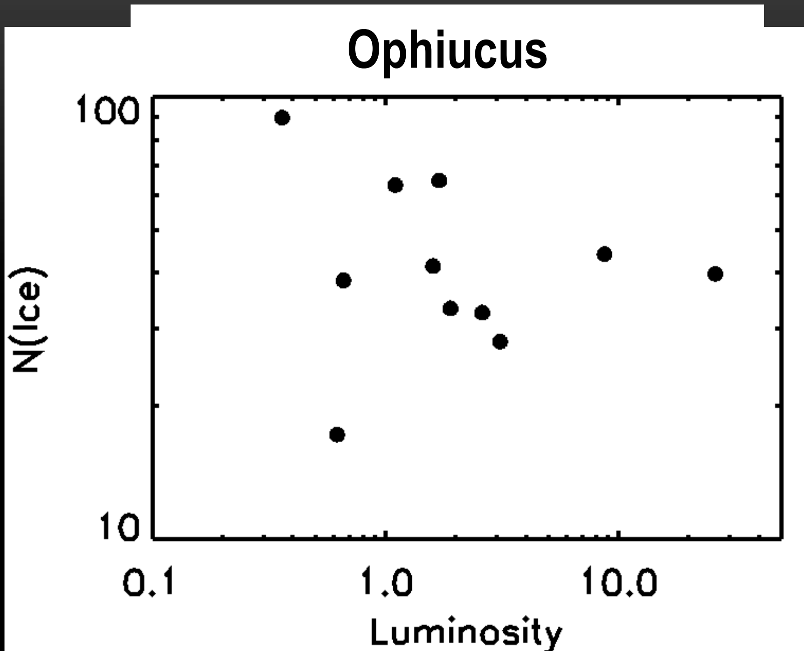
Evolution of Ices around Embedded YSOs

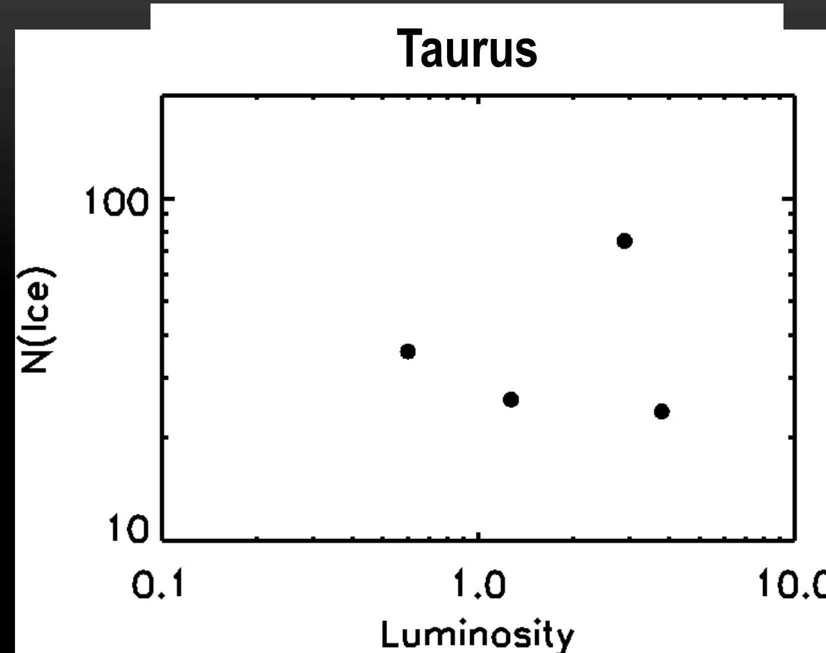


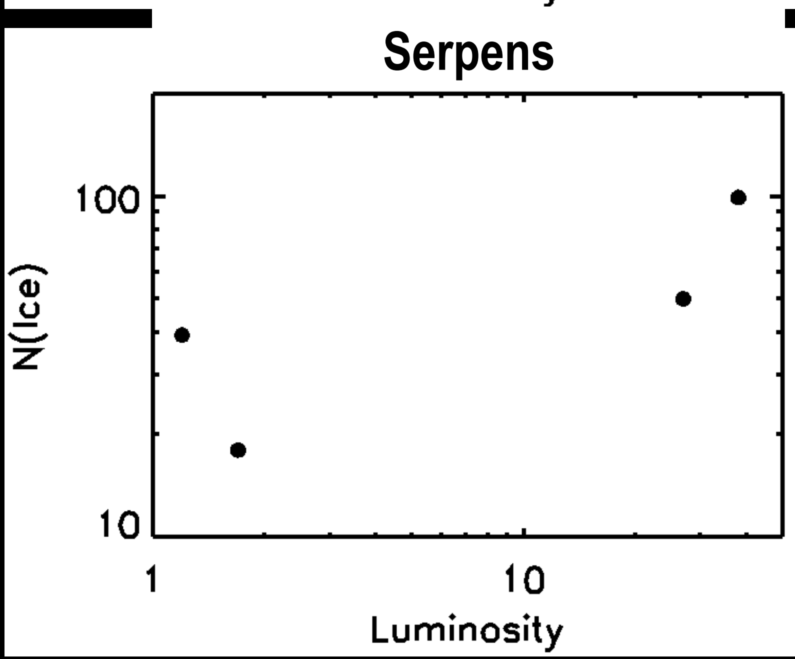
- Stellar radiation does chemical abundance YSOs
- Environmental factor the chemical evolutio



N(ice) vs. Luminosity, for low-mass YSOs







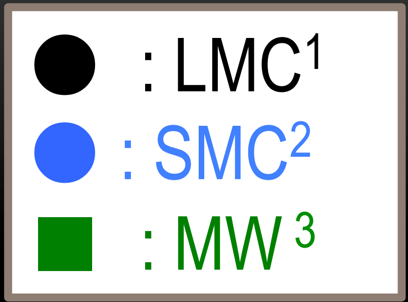
N(ice) vs. luminosity relation is not clear for Galactic low-mass YSOs

Ice data: Whittet et al. 2011

Luminosity:

Bontemps et al. 2001
Chen et al. 1995
Furlan et al. 2008
Kaas et al. 2004
Pontoppidan et al. 2004
Saraceno et al. 1996

Ice Column density vs. Luminosity, Effect of Metallicity



1. Shimonishi+ 2010
2. Shimonishi+ in prep.
   Oliveira+2010
3. Gibb+ 2004

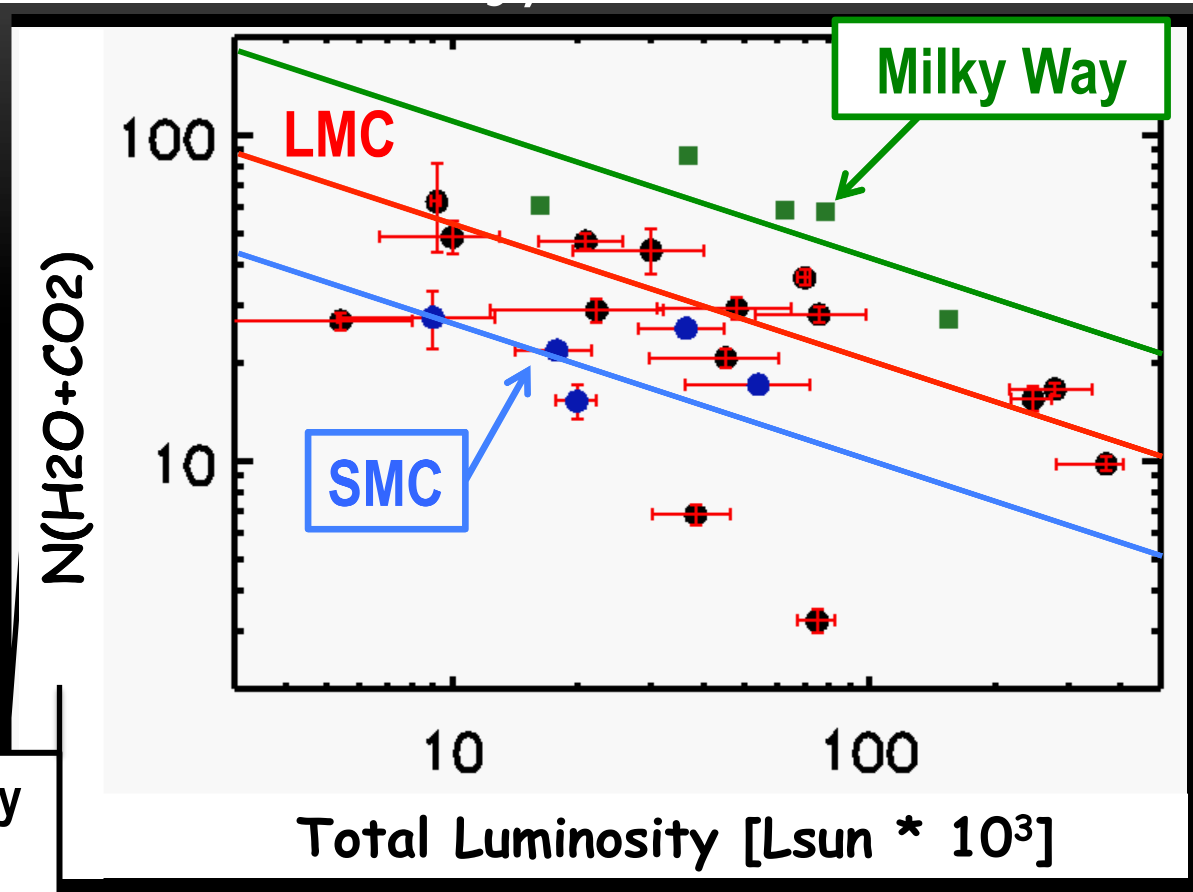
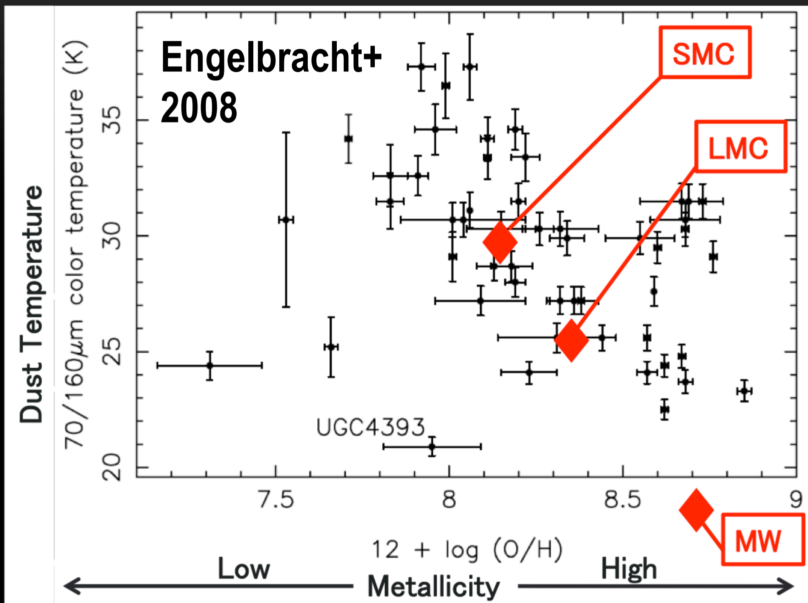


Fig.23 Ice column density vs. Luminosity of a YSO

The total column density of ices decreases with decreasing metallicity of the parent galaxiy

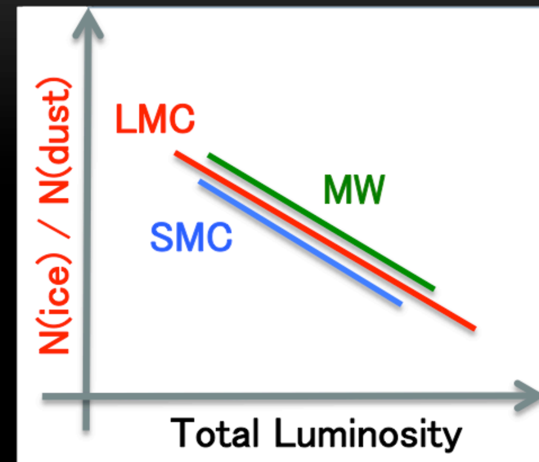
Two Hypotheses

~Why does ice column density decrease with decreasing metallicity?~



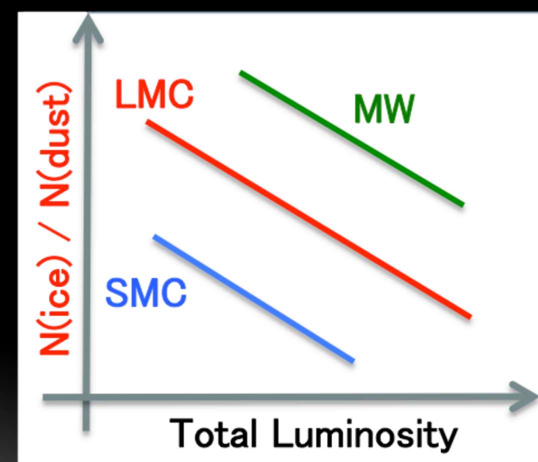
and

re



- Hypothesis 2

--- Ices sublimate due to high dust temperature in metal-poor galaxies



Key: Dust Column Density

Fig.24 Two hypotheses

Analyzing MIR Spectra of YSOs

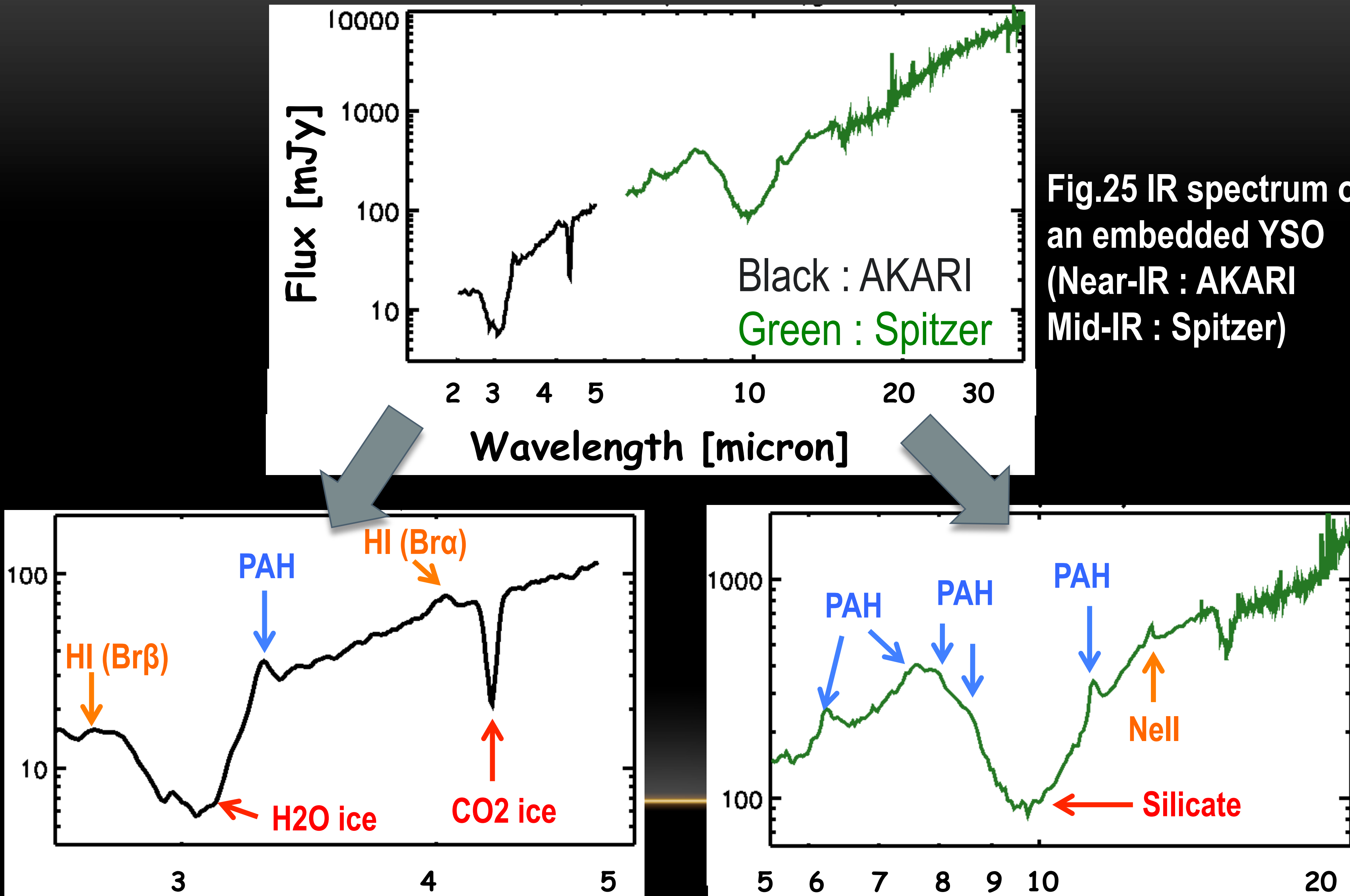
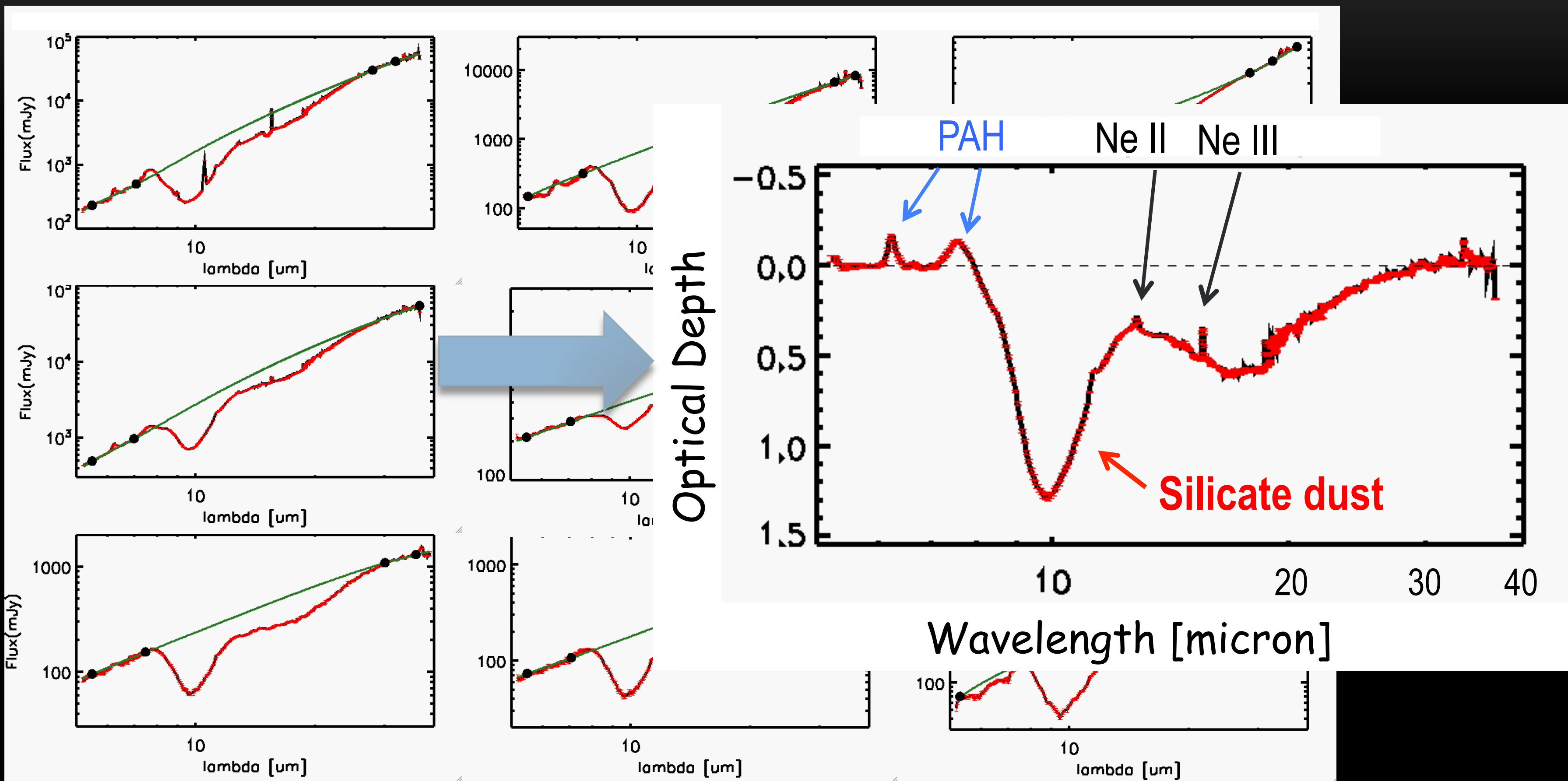


Fig.25 IR spectrum of an embedded YSO (Near-IR : AKARI Mid-IR : Spitzer)

MIR 10 micron dust feature

- Spitzer IRS[1] and Gemini South T-ReCS were used



[1]Spitzer data was taken from Spitzer Heritage Archive

Fig.26 Spitzer/IRS MIR spectra of Magellanic YSOs

N(ice)/Av vs. Luminosity

● : LMC[1]
● : SMC[2]
■ : MW[3]

1. Shimonishi+ 2010
2. Shimonishi+ in prep.
   Oliveira+2010
3. Gibb+ 2004

$A_V = 18.5 \times \tau_{9.7}$
relation adapted[1]

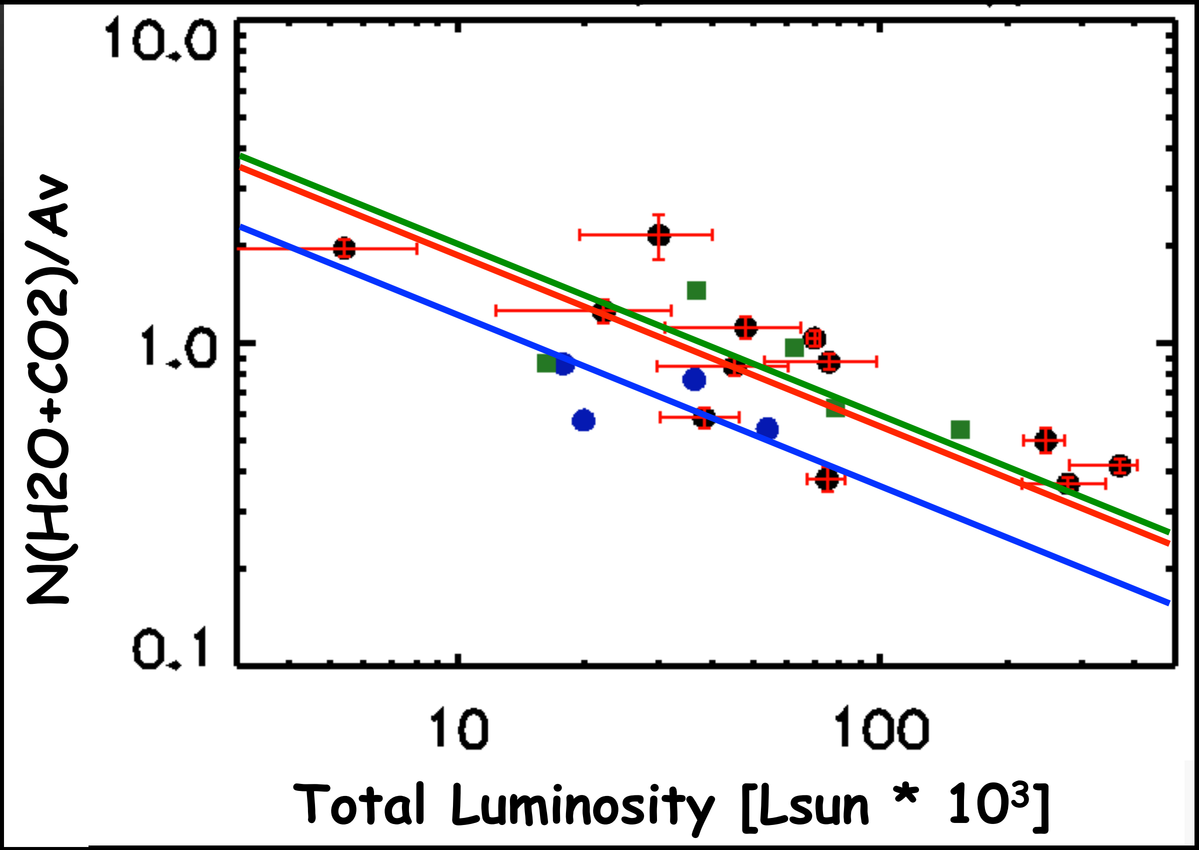
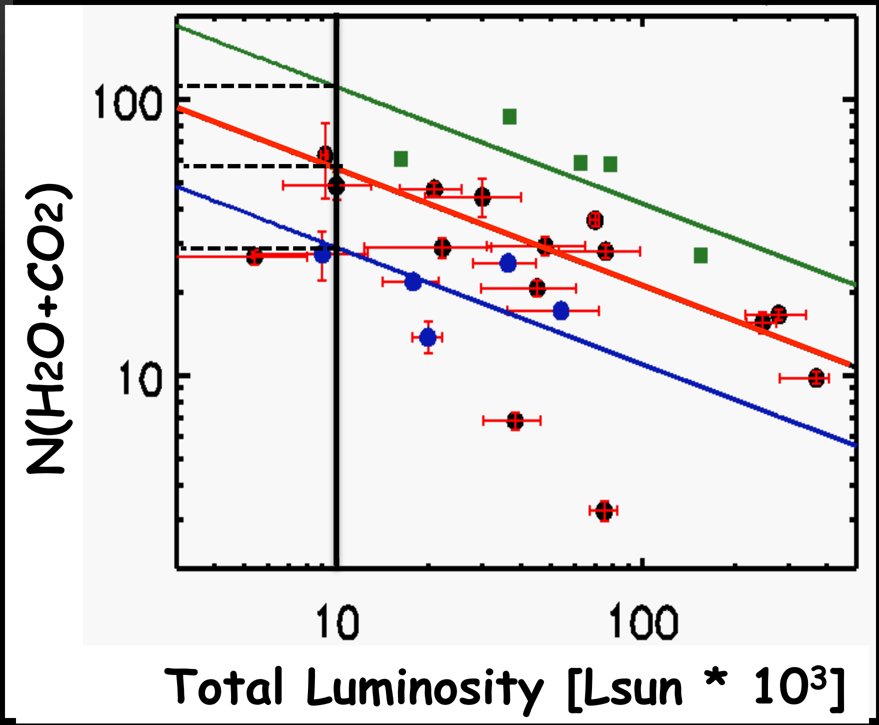


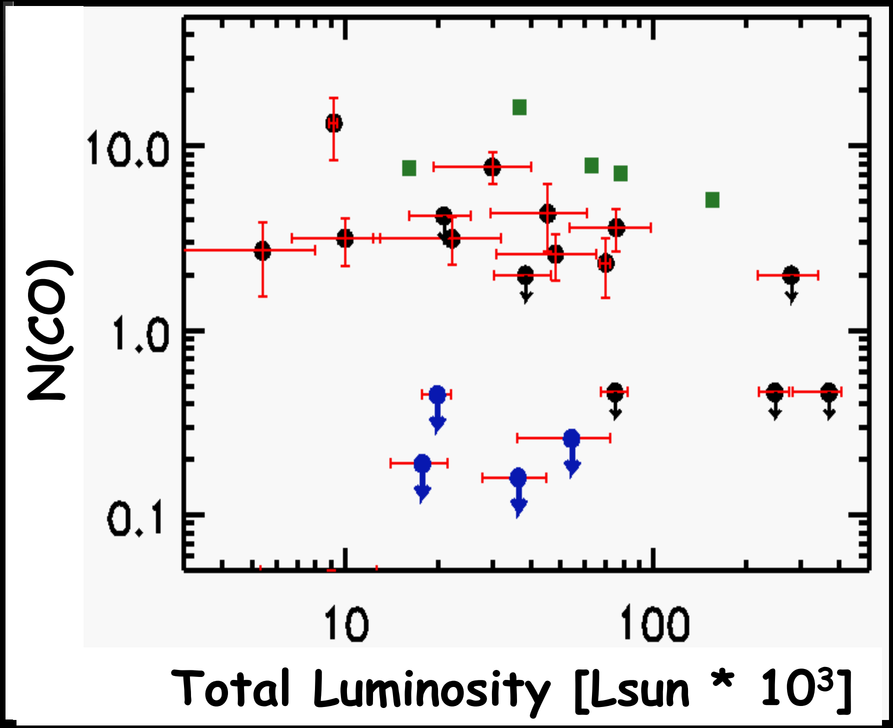
Fig.27 Ice column density / silicate optical depth vs. Luminosity

Amount of ices around YSOs is scaled by the amount of dust

[1]Tielens et al. 2005

N(ice) vs. Luminosity





- : LMC[1]
- : SMC[2]
- : MW[3]

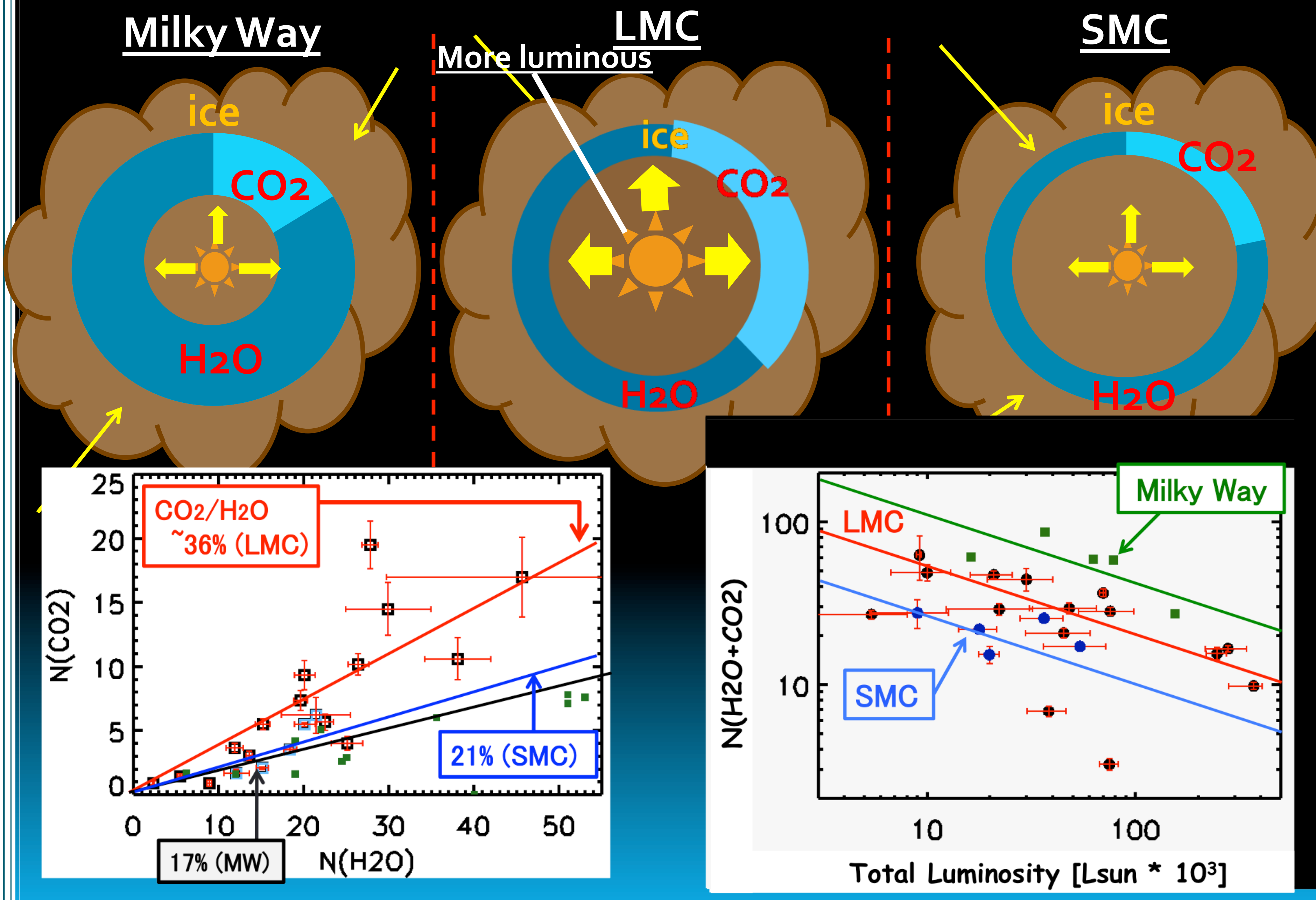
1. Shimonishi+ 2010
2. Shimonishi+ in prep.
   Oliveira+2010
3. Gibb+ 2004

$N(H_2O+CO_2)$ at L = $10^4 M_\odot$
… MW : LMC : SMC = 112 : 56 : 30 ～ 1 : 0.5 : 0.3
Metallicity … MW : LMC : SMC ～ 1 : 0.5 : 0.2

Low N(CO) in the SMC cannot be explained by the metallicity
… Effect of temperature may contributes

Fig.28 Ice column density vs. Luminosity

Effect of galactic environment on YSO's ices



SUMMARY

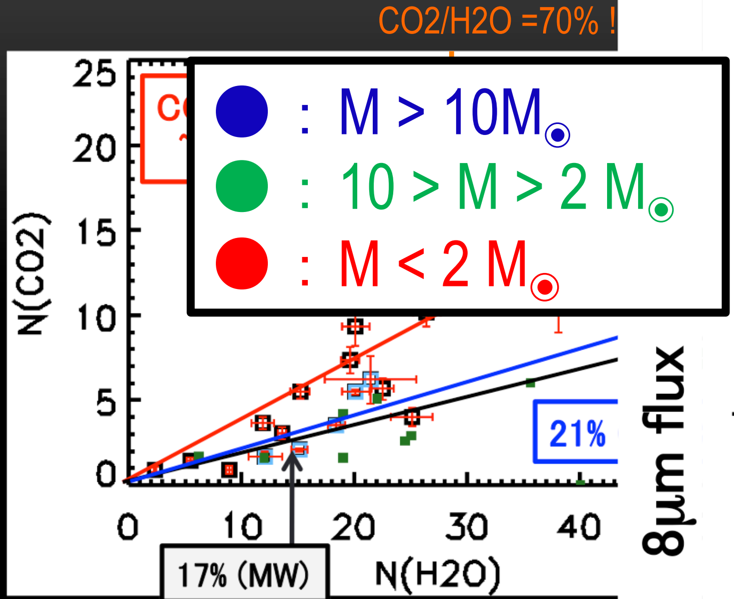
- ✓ Spectroscopic studies of extragalactic YSOs have progressed greatly in these few years, and more than 20 YSOs are observed in the Magellanic Clouds with AKARI and Spitzer
- ✓ Comparative study of ices around Galactic and Magellanic YSOs is now possible in terms of sample number and spatial resolution

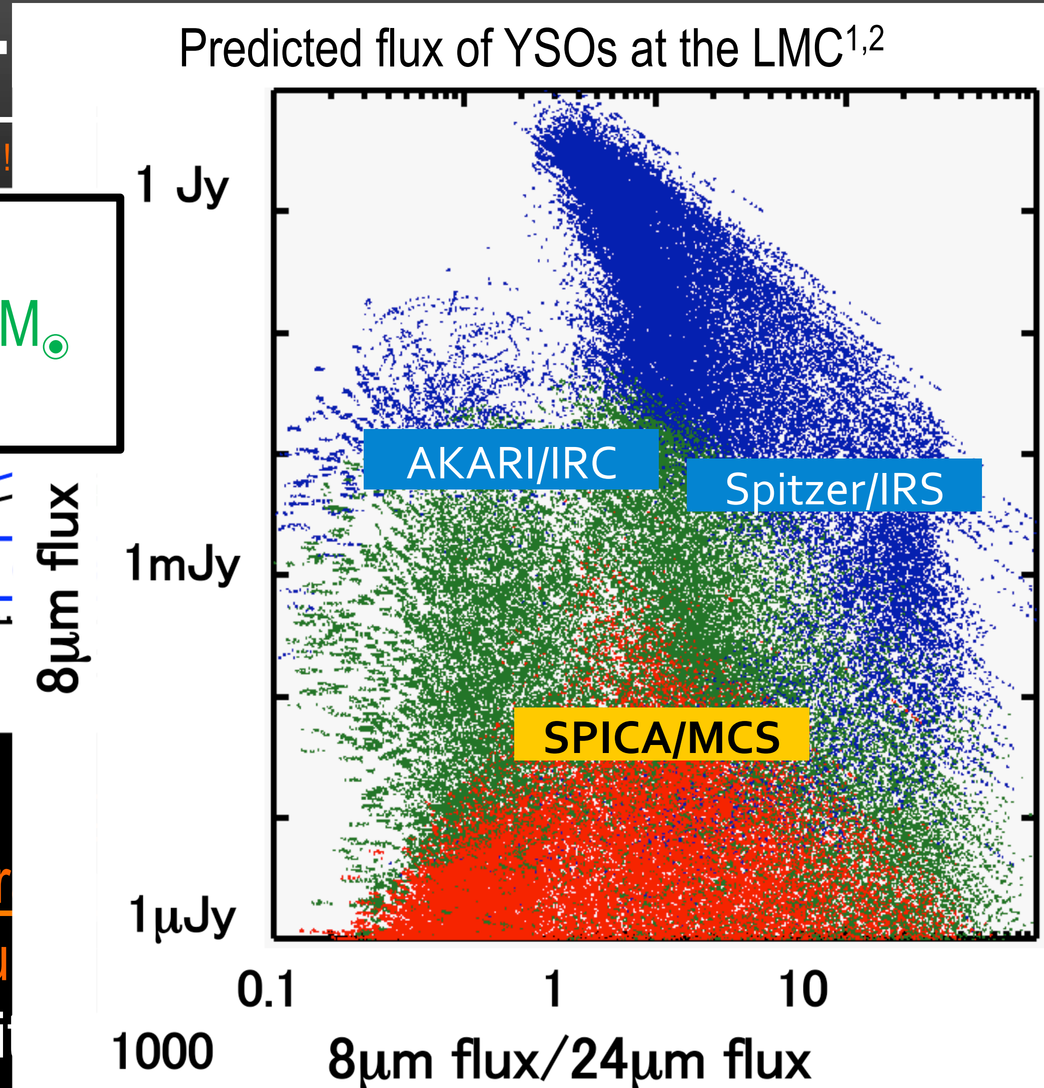
What is the difference between Milky Way's YSOs and Magellanic YSOs?

↓

- ✓ Molecular abundance of CO_2 ice is systematically higher in the LMC
- ✓ No CO ice detection in the SMC
- ✓ Ice column density decreases as metallicity decreases
- ✓ Ice column density shows strong correlation with YSO's luminosity

FUT





- ✓ Ice observations of
  - ➡ Chemistry in Extr
- ✓ Gas-phase molecu
  - ➡ Effect of metallicit
- ✓ Observations of minor ice species (e.g., CH3OH)
- ✓ Theoretical study to reproduce the above results

[1]Robitaille et al. 2006 [2]SPICA MIR fact sheet

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