Quest to understand the origin of the Solar system

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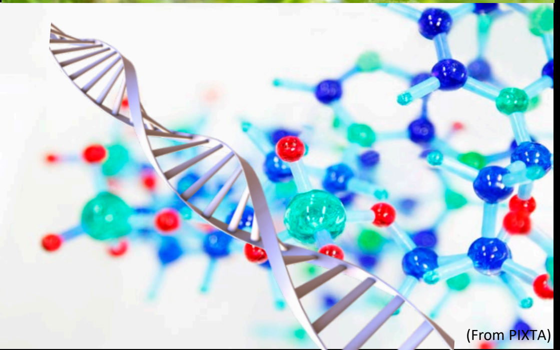
RIKEN Pioneering Research Project "Evolution of Matter in the Universe (r-EMU)" FY2019-FY2023

(From PIXTA)



(From PIXTA)

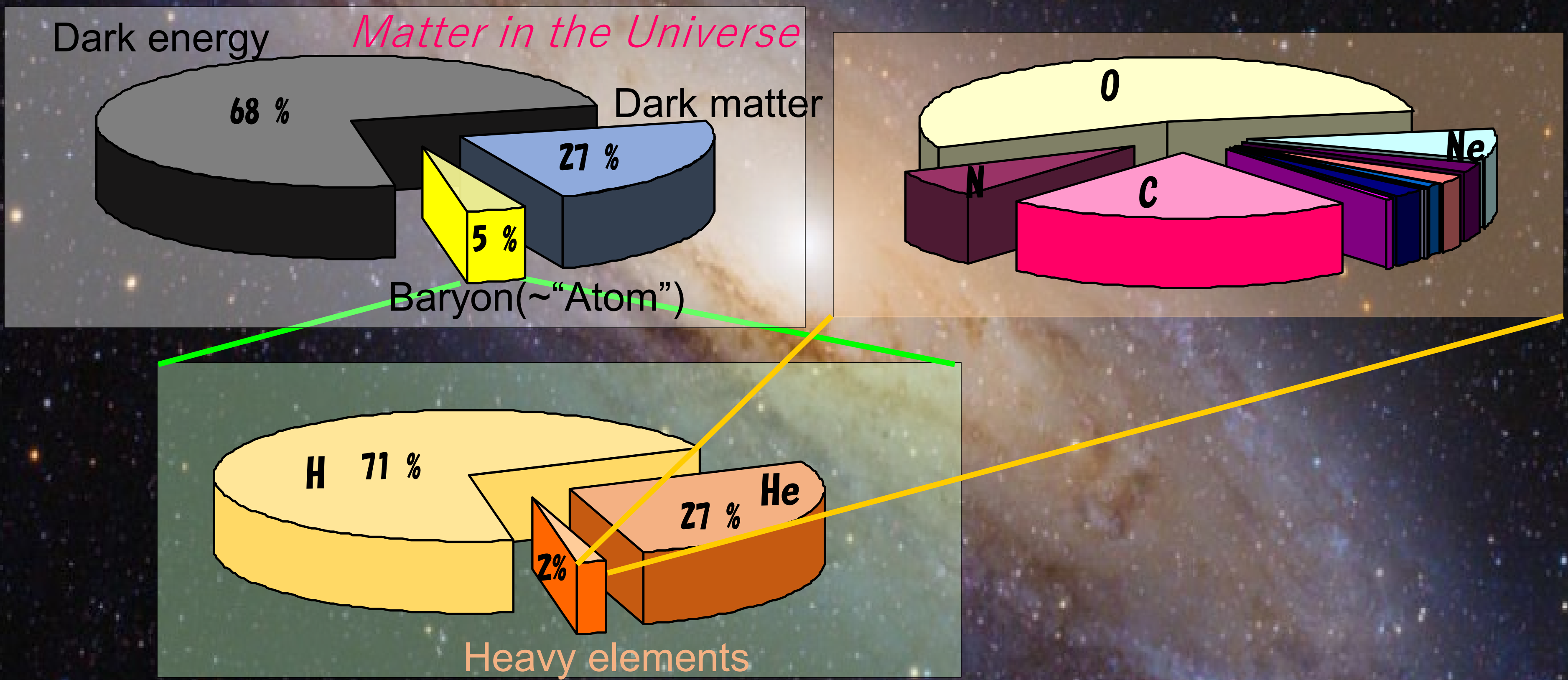
Existence of "life"
Common or Miracle?

(From NASA)

"Where do we come from?"

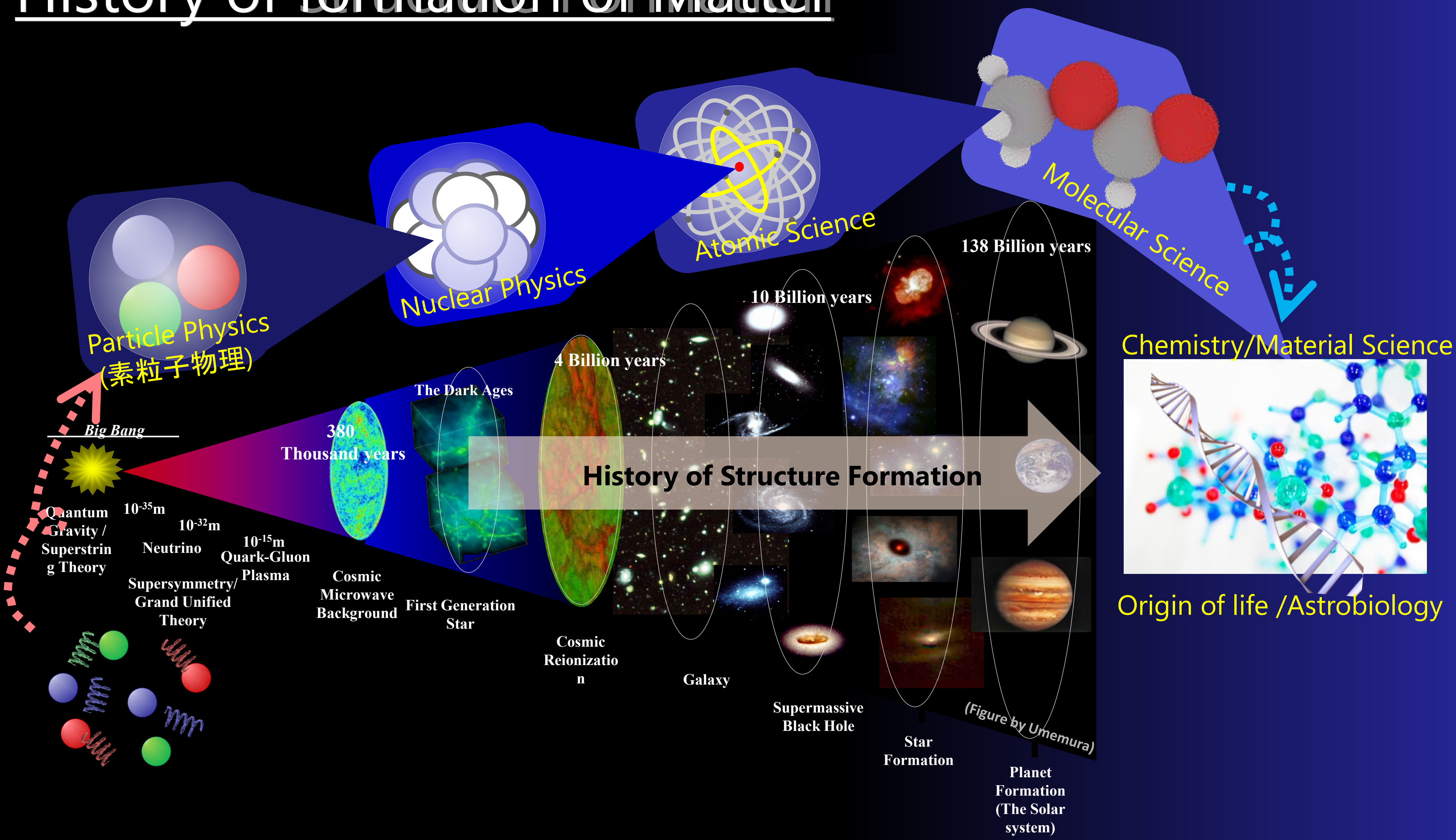
→ "How did we get here?"

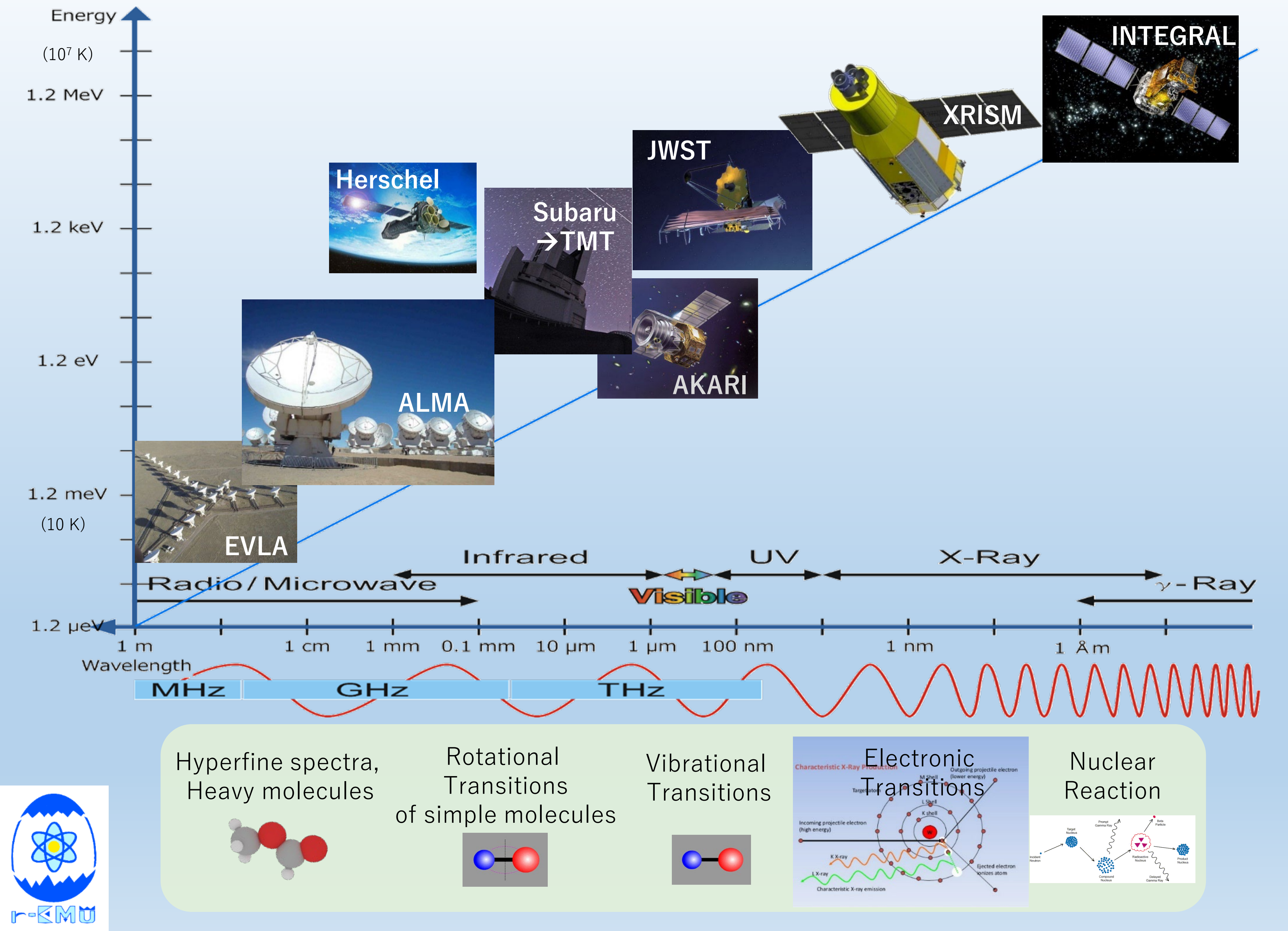
Why Baryon?



Dark energy
Matter in the Universe
68 %
Dark matter
27 %
5 %
Baryon(~"Atom")
O
Ne
N
C
H 71 %
He
27 %
2%
Heavy elements

History of formation of Matter





Energy
(10^7 K)
1.2 MeV
1.2 keV
1.2 eV
1.2 meV
(10 K)
1.2 μeV
INTEGRAL
XRISM
JWST
Herschel
Subaru
→TMT
AKARI
ALMA
EVLA
Infrared
UV
X-Ray
Radio / Microwave
Visible
γ - Ray
1 m
1 cm
1 mm
0.1 mm
10 μm
1 μm
100 nm
1 nm
1 Å m
Wavelength
MHz
GHz
THz
Hyperfine spectra,
Heavy molecules
Rotational
Transitions
of simple molecules
Vibrational
Transitions
Electronic
Transitions
Nuclear
Reaction
r-EMU

Molecules in Space (~275 species)

2 Atoms (42 Species)

H_2, CO, AlF, AlCl, C_2, CH, CH^+, CN, CO^+, CP, SiC, HCl, KCl, NH, NO, NO^+(?), NS, NS^+, NaCl, OH, PN, SO, SO^+, SiN, SiO, SiS, CS, HF, HD, FeO (?), O_2, CF^+, SiH (?), PO, PO^+, AlO, OH^+, CN^-, SH^+, SH, HCl^+, TiO, ArH^+, HeH^+, NO^+ (?), N_2

3 Atoms (40 Species)

C_3, C_2H, C_2O, C_2S, CH_2, HCN, HCO, HCO^+, HCS^+, HOC^+, H_2O, H_2S, HNC, HNO, MgCN, MgNC, N_2H^+, N_2O, NaCN, OCS, SO_2, c-SiC_2, CO_2, NH_2, H_3^+, SiCN, AlNC, SiNC, HCP, CCP, AlOH, H_2O^+, H_2Cl^+, KCN, FeCN, HO_2, TiO_2, C_2N, Si_2C, HS_2, HCS, HSC, HNO, CaNC, NCS

4 Atoms (27 Species)

c-C_3H, l-C_3H, C_3N, C_3O, C_3S, C_2H_2, NH_3, HCCN, $HCNH^+$, HNCO, HNCS, $HOCO^+$, H_2CO, H_2CN, H_2CS, H_3O^+, c-SiC_3, CH_3, C_3N^-, PH_3, HCNO, HOCN, HSCN, H_2O_2, C_3H^+, HMgNC, HCCO, CNCN, HONO, MgC_2H, HCCS, HNCN, H_2NC, $HCCS^+$

5 Atoms (23 Species)

C_5, C_4H, C_4Si, *l*-C_3H_2, c-C_3H_2, H_2CCN, CH_4, HC_3N, HC_2NC, HCOOH, H_2CNH, H_2C_2O, H_2NCN, HNC_3 , SiH_4, H_2COH^+, C_4H^-, HC(O)CN, HNCNH, CH_3O, NH_4^+, H_2NCO^+ , $NCCNH^+$, CH_3Cl, MgC_3N, NH_2OH, HC_3O^+, HC_3S^+, H_2C_2S, C_4S, HC(O)SH, HC(S)CN, HCCCO

Highly unsaturated species (Carbon-chain molecules: **CCMs**)

↓**iCOMs** (interstellar "Complex" Organic Molecules)

6 Atoms (17 Species)

C_5H, *l*-C_4H_2, C_2H_4, CH_3CN, CH_3NC, CH_3OH, CH_3SH, HC_3NH^+, HC_2CHO, NH_2CHO, C_5N, l-HC_4H, l-HC_4N, c-H_2C_3O, H_2CCNH, C_5N^-, HNCHCN, SiH_3CN, C_5S, MgC_4H, CH_3CO+, C_3H_3, H_2C_3S, HCCCHS, C_5O, C_5H^+, $HCCNCH^+$

7 Atoms (10 Species)

C_6H, CH_2CHCN, CH_3C_2H, HC_5N, CH_3CHO, CH_3NH_2, c-C_2H_4O, H_2CCHOH, C_6H^-, CH_3NCO, HC_5O, $HOCH_2CN$, HCCCHNH, HC_4NC, c-C_3HCCH, l-C_5H_2, MgC_5N, CH_2C_3N

8 Atoms (11 Species)

CH_3C_3N, HC(O)OCH_3, CH_3COOH, C_7H, C_6H_2, CH_2OHCHO, l-HC_6H, CH_2CHCHO , CH_2CCHCN, H_2NCH_2CN, CH_3CHNH, CH_3SiH_3, $H_2NC(O)NH_2$, $HCCCH_2CN$, HC_5NH^+, CH_2CHCCH, MgC_6H, $C_2H_3NH_2$, $(CHOH)_2$

9 Atoms (10 Species)

CH_3C_4H, CH_3CH_2CN, $(CH_3)_2O$, CH_3CH_2OH, HC_7N, C_8H, $CH_3C(O)NH_2$, C_8H^-, C_3H_6, CH_3CH_2SH, CH_3CH_2SH, CH_3NHCHO, HC_7O, HCCCHCHCN, H_2CCHC_3N, $H_2CCCHCCH$, HOCHCHCHO(?)

10 Atoms (5 Species)

CH_3C_5N, $(CH_3)_2CO$, $(CH_2OH)_2$, CH_3CH_2CHO, CH_3CHCH_2O, CH_3OCH_2OH, c-C_6H_4, H_2CCCHC_3N, C_2H_5NCO, $C_2H_5NH_2$(?), HC_7NH^+

11 Atoms (4 Species)

HC_9N, CH_3C_6H, C_2H_5OCHO, $CH_3OC(O)CH_3$, $CH_3C(O)CH_2OH$, c-C_5H_6, $HOCH_2CH_2NH_2$

12 Atoms (4 Species)

c-C_6H_6, n-C_3H_7CN, i-C_3H_7CN, $C_2H_5OCH_3$, 1-c-C_5H_5CN, 2-c-C_5H_5CN, CH_3C_7N(?), n-C_3H_7OH, i-C_3H_7OH

>12 Atoms (3 Species)

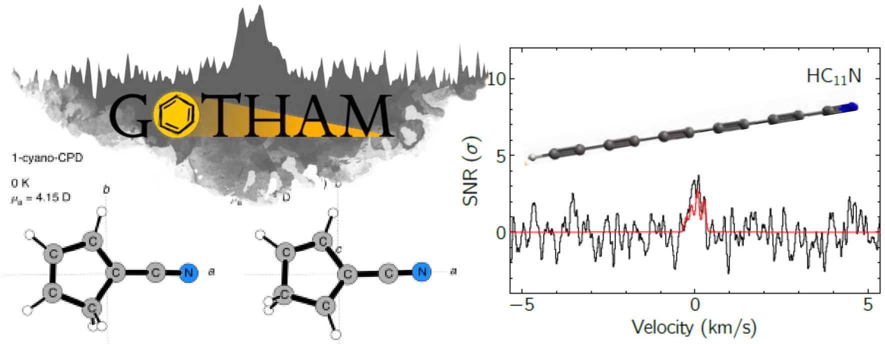
C_{60}, C_{70}, C_{60}^+, c-C_6H_5CN, $HC_{11}N$, 1-$C_{10}H_7CN$, 2-$C_{10}H_7CN$, c-C_9H_8, 1-c-C_5H_5CCH, 2-c-C_5H_5CCH

Mainly detected by radio observations

(Gray: Detected only toward AGB stars)

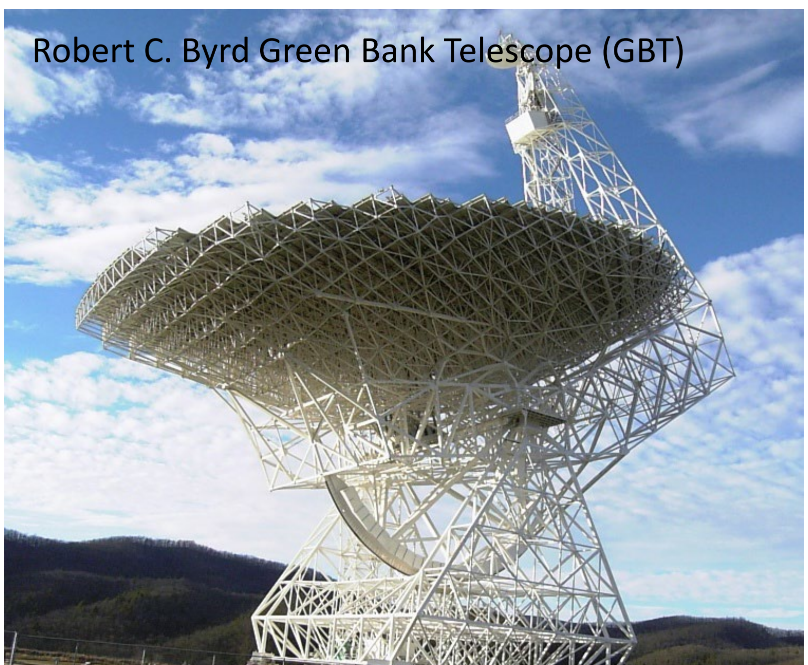
(The Cologne Database for Molecular Spectroscopy (CDMS): June. 2022)

GBT Observations of TMC-1: Hunting Aromatic Molecules (GOTHAM)

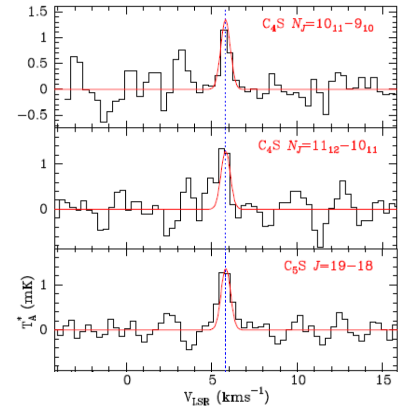


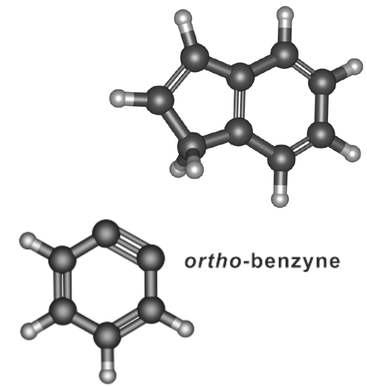
PI: Brett A. McGuire

(e.g. McGuire, B. A., et al. 2020, ApJ, 900, L10;
McCarthy, M. C., et al. 2021, Natur., 5, 176
Loomis, R. A., et al. 2021, Natur. Astro., 5, 188)


Robert C. Byrd Green Bank Telescope (GBT)

QUIJOTE: Q-band Ultrasensitive Inspection Journey to the Obscure TMC-1 Enviroment: Discovering the limits of chemical complexity

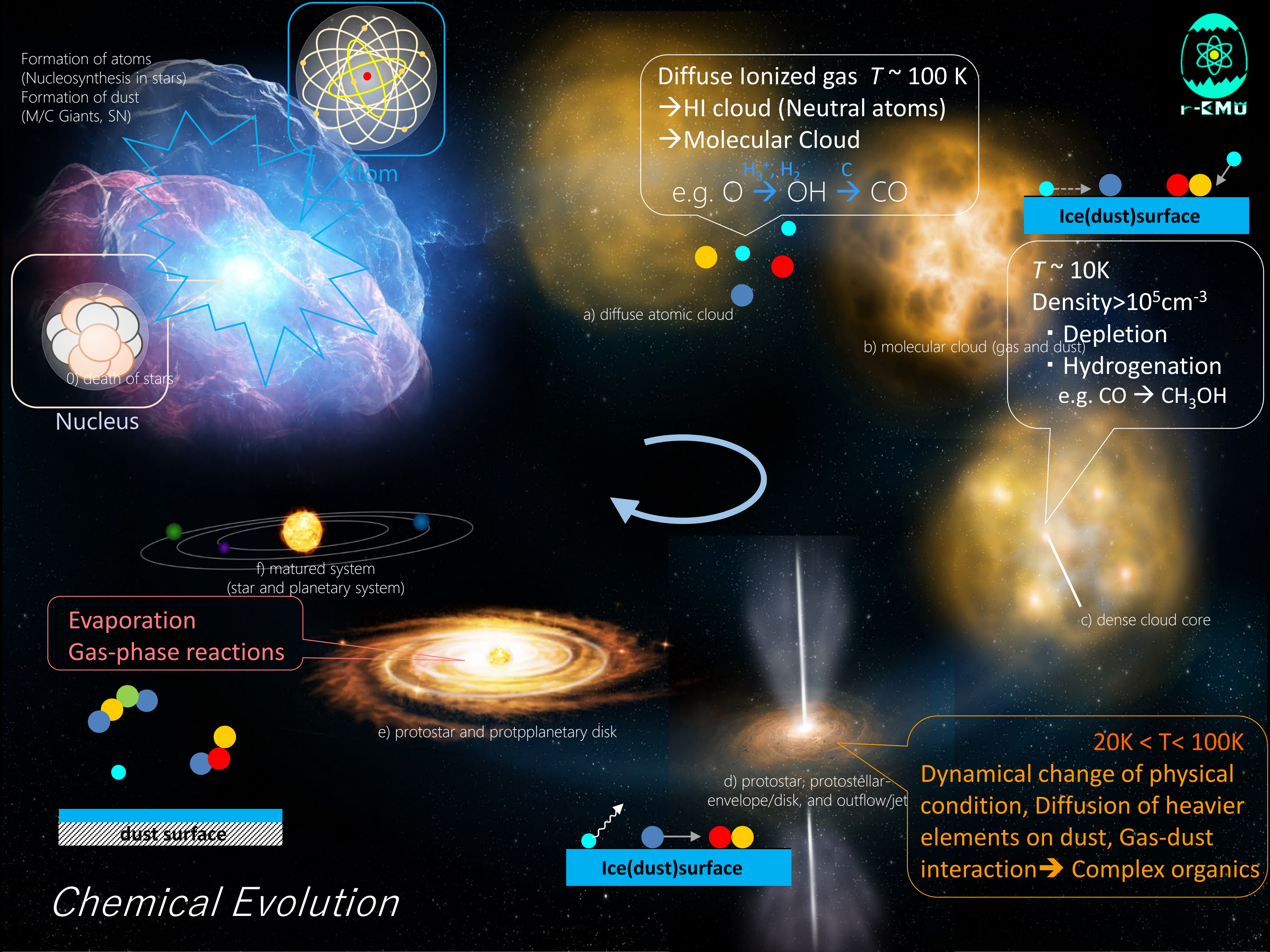




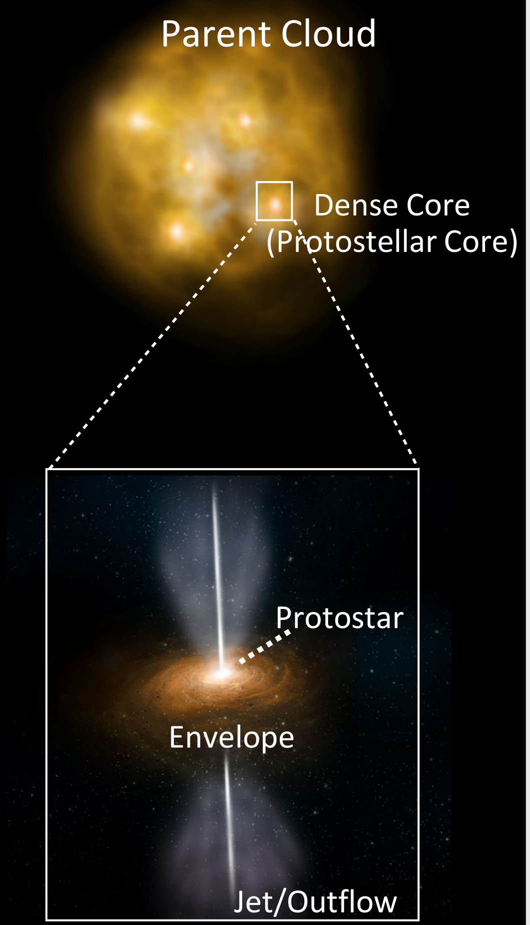
PI: Jose Cernicharo

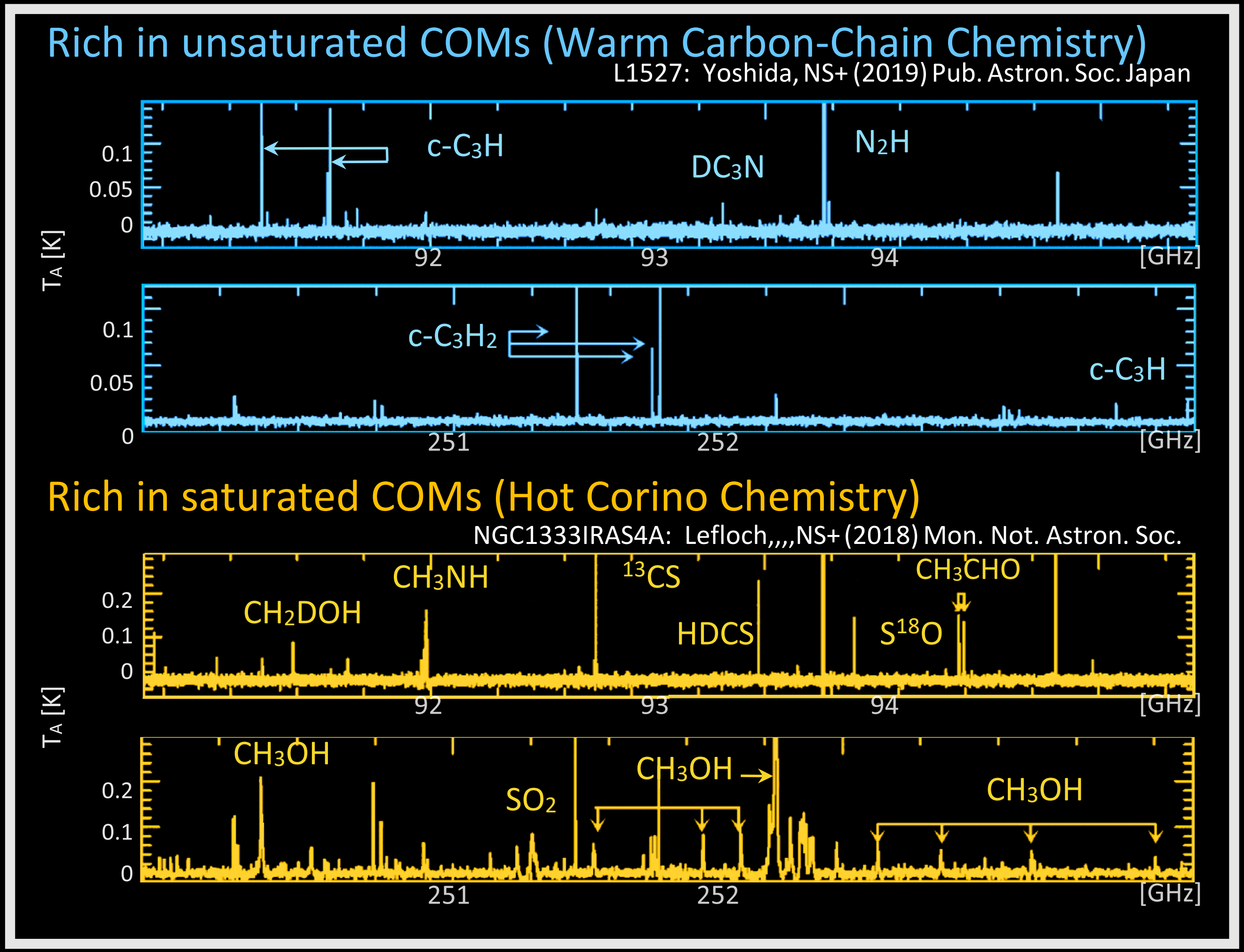
(Guélin, Michel & Cernicharo, Jose, 2022, Frontiers in Astronomy and Space Sciences, vol. 9, id. 787567, and references therein)


The 40-m Yebes telescope –credit: Pablo deVicente


Formation of atoms
(Nucleosynthesis in stars)
Formation of dust
(M/C Giants, SN)
Atom
Nucleus
0) death of stars
Diffuse Ionized gas T ~ 100 K
→HI cloud (Neutral atoms)
→Molecular Cloud
e.g. O → OH → CO
H_3^+, H_2
C
a) diffuse atomic cloud
Ice(dust)surface
b) molecular cloud (gas and dust)
T ~ 10K
Density>$10^5 cm^{-3}$
・Depletion
・Hydrogenation
e.g. CO → CH_3OH
c) dense cloud core
f) matured system
(star and planetary system)
Evaporation
Gas-phase reactions
e) protostar and protpplanetary disk
d) protostar, protostellar-envelope/disk, and outflow/jet
20K < T< 100K
Dynamical change of physical condition, Diffusion of heavier elements on dust, Gas-dust interaction→ Complex organics
dust surface
Ice(dust)surface
Chemical Evolution

Chemical Composition in Cloud-Core (Envelope) Scale

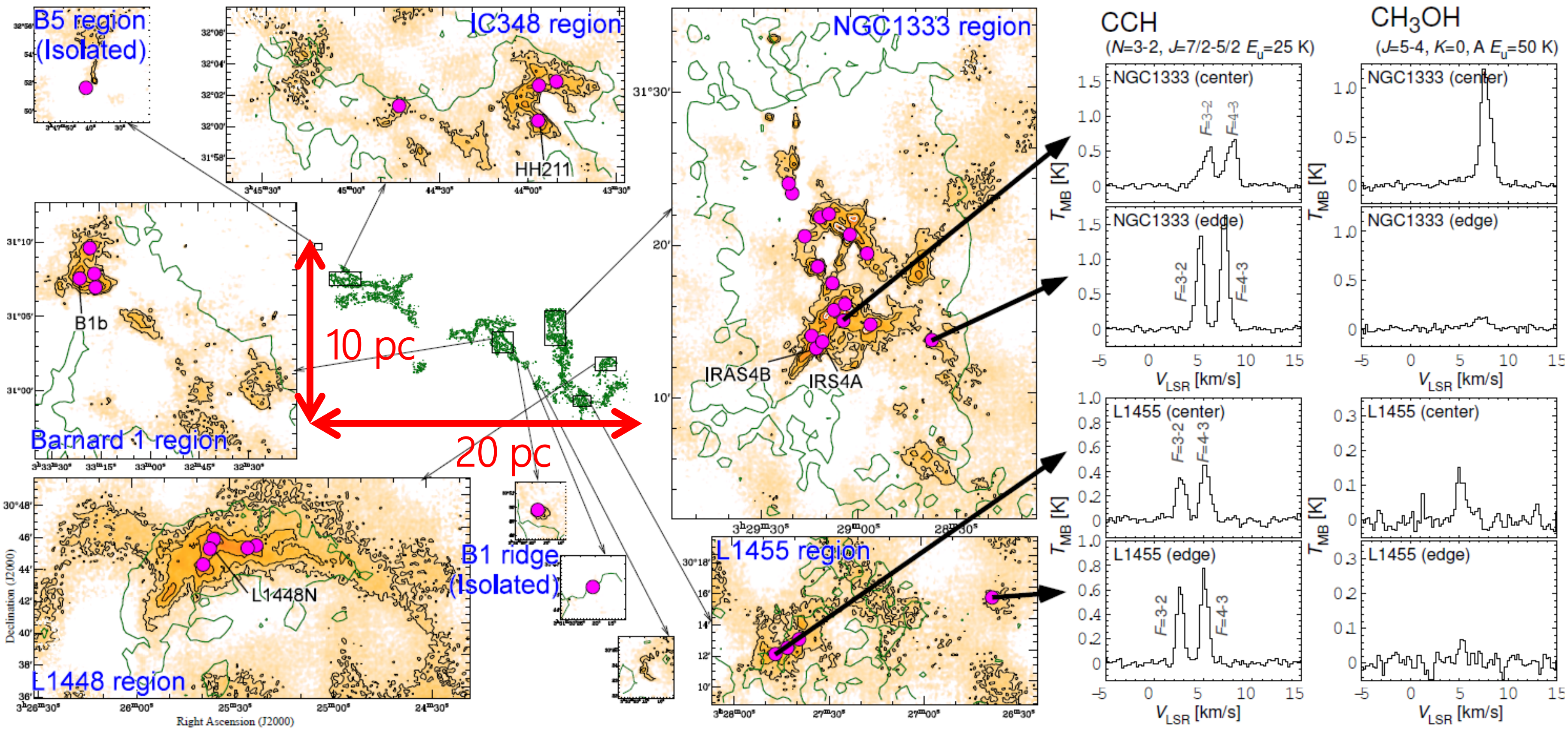




Which is the dominant case ? Which is the case for our solar system??

Perseus Chemical Survey

Exploring core (~5,000 au) scale diversity
(Nobeyama 45 m + IRAM 30 m survey toward Class0/I sources@2014-2016)

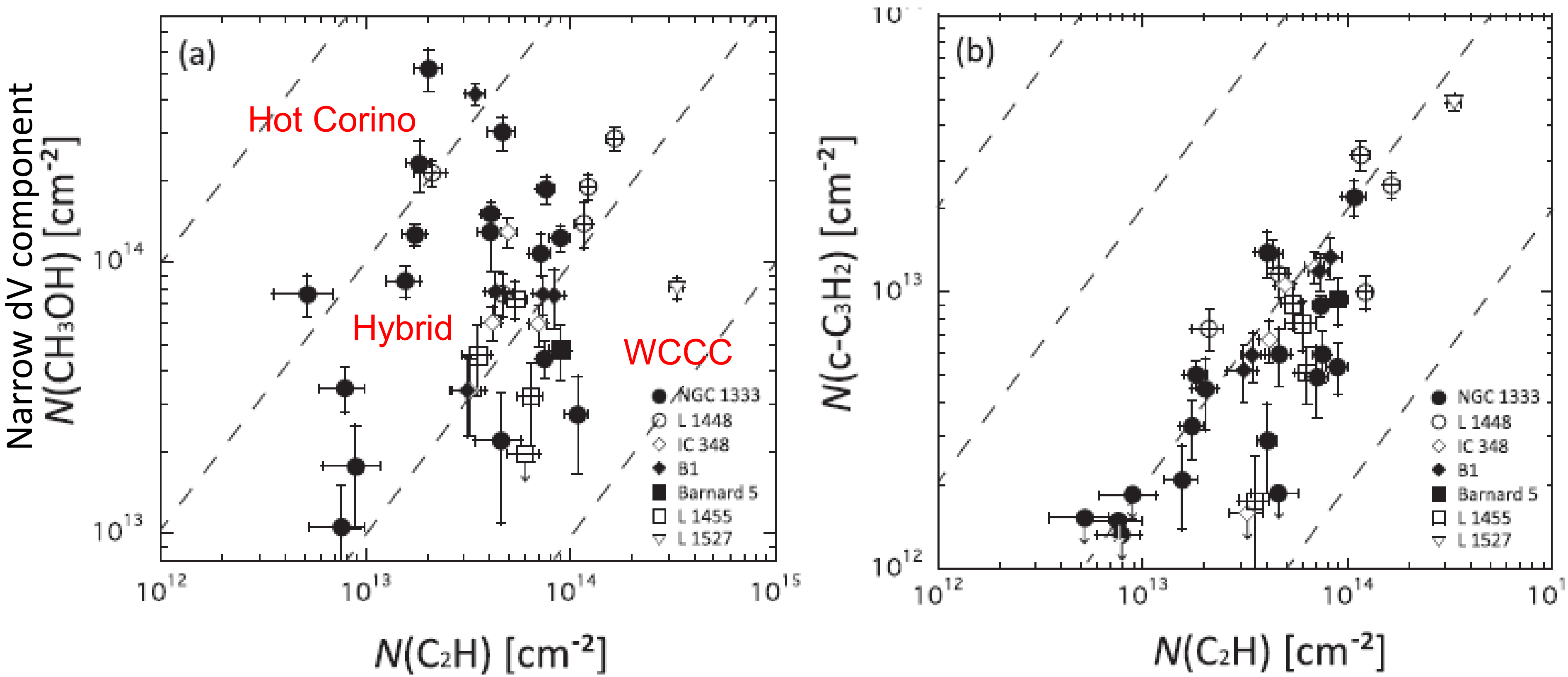


Orange: Dust, Green Contour: CO
(Hatchell et al. 2005, A&A, 440, 141; 2007, A&A, 468, 1009)

(Higuchi, NS et al. 2018, ApJS, 236, 52)

Chemical Diversity in Perseus

Diversity in envelope size scale (~5,000 au)



How about in protoplanetary-disk size scale ?
~100 au

(Higuchi, NS et al. 2018, ApJS, 236, 52)

Radio Telescope：Lower Spatial Resolution

Single-Dish： a few 10s arcsec cf; SUBARU (Infrared-Optical)：0.2-0.02 arcsec

ドイツ: MPIfR 100 m電波望遠鏡

The Robert C. Byrd Green Bank Telescope, commonly known as the GBT

Scientists take lemons and make lemonade.

The NRAO was able to do more than just replace the 300-foot telescope. In fact, the loss of the big dish became a catalyst for a totally new, unconventional telescope design. The GBT's offset optics and active surface are unique among large radio telescopes. The GBT is the world's largest, fully steerable radio telescope.

United States Senator Robert C. Byrd helped secure congressional funding for the telescope project.

Think you're having a bad day? Sometimes telescopes have them too!

NRAO, Green Bank, West Virginia

9:43 p.m., Tuesday, November 15, 1988

Green Bank's largest telescope collapsed.

Metal fatigue in the antenna's support was determined to be the cause. After delivering 26 years of service (far beyond its life expectancy) the 300-foot diameter telescope dish sank to its foundation, beyond repair.

The loss of the 300-foot telescope resulted in the Green Bank Telescope Project.

BEFORE

AFTER

ALMA: Atacama Large Millimeter/sub-millimeter Array

High angular resolution
1” → <0.01”-0.1”

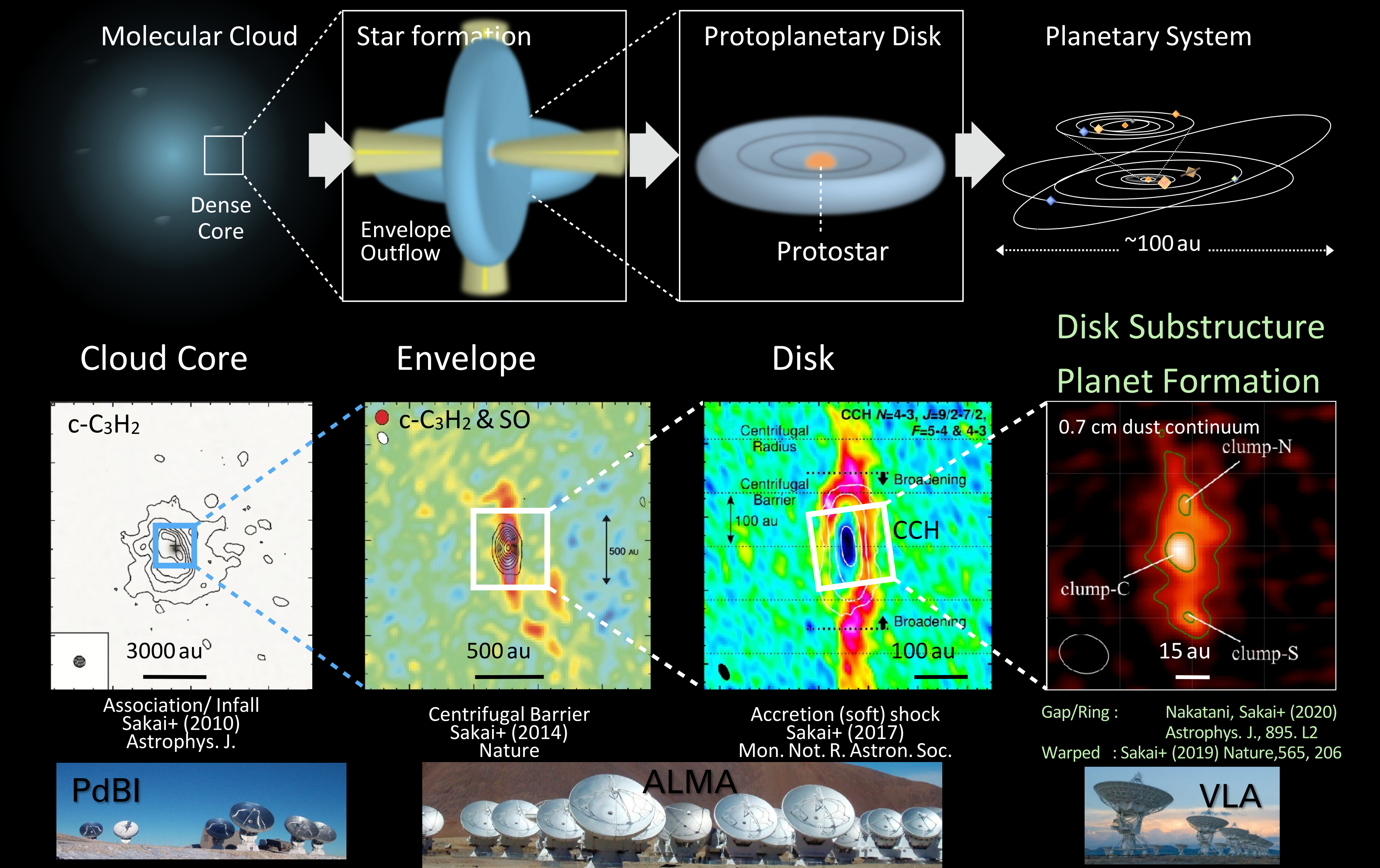
High sensitivity
100 hours → 10 min.

7 mm – 0.4 mm
(40 – 940 GHz)

Main antenna : 12 m x 50
ACA antenna: 12 m x 4, 7 m x 12
Total:66

2014, full operation started
Europe, North America, and East Asia in cooperation with Chile

Formation of Planetary System & Observational Challenges



PEACHES

PErseus ALMA CHEmical Survey

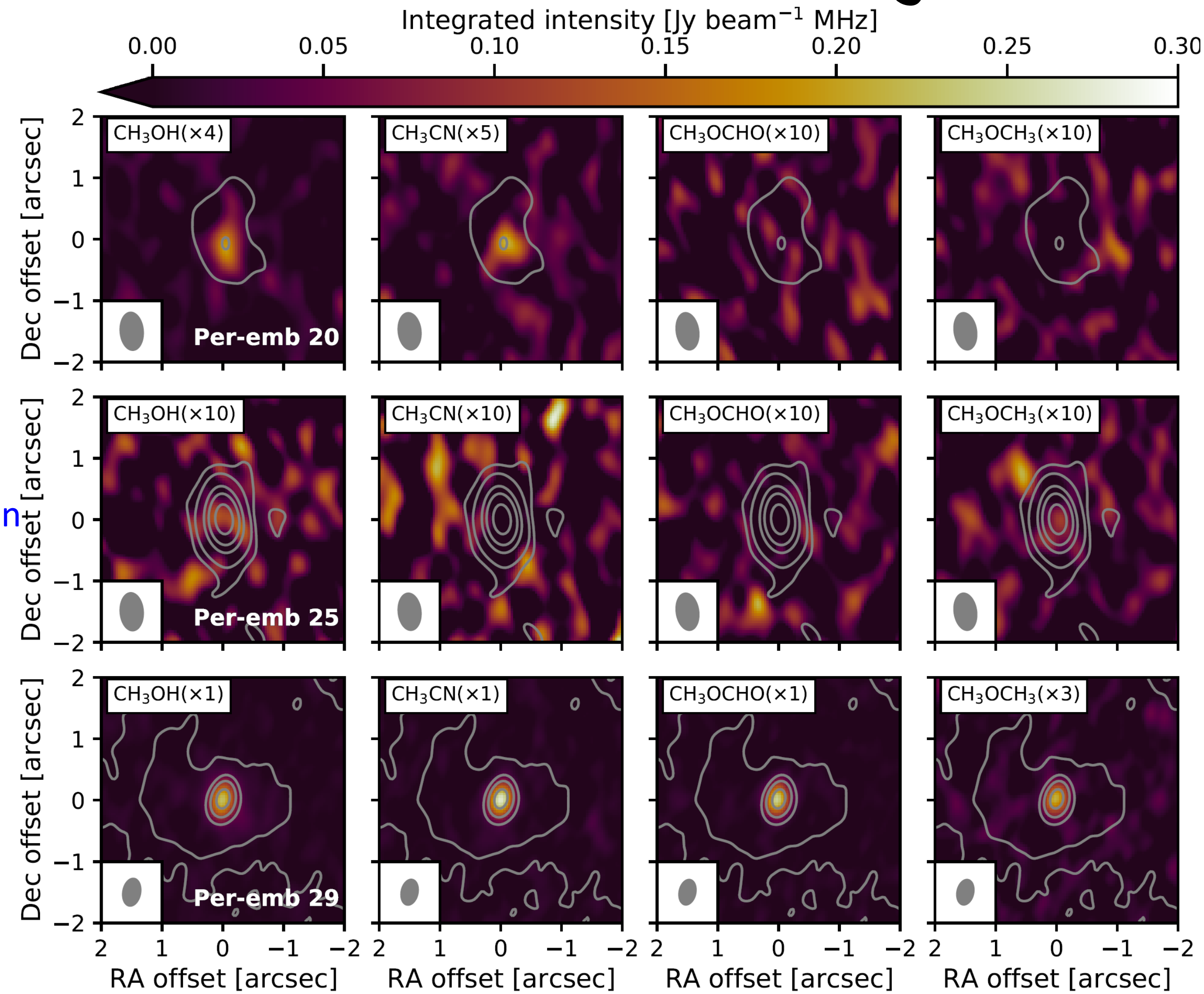
Next Generation Astrochemistry

ALMA data:
PI Sakai
~50 YSOs
in Perseus
d~300 pc

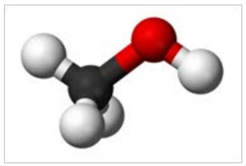
Weakest cont.

Strong cont.
COMs non-detection
(SO/SO_2 detection)

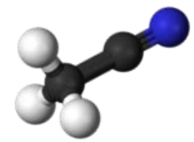
Strongest cont.



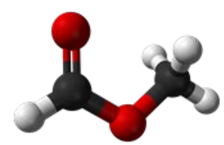
Methanol



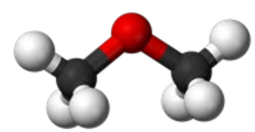
Acetonitrile



Methyl formate



Dimethyl ether



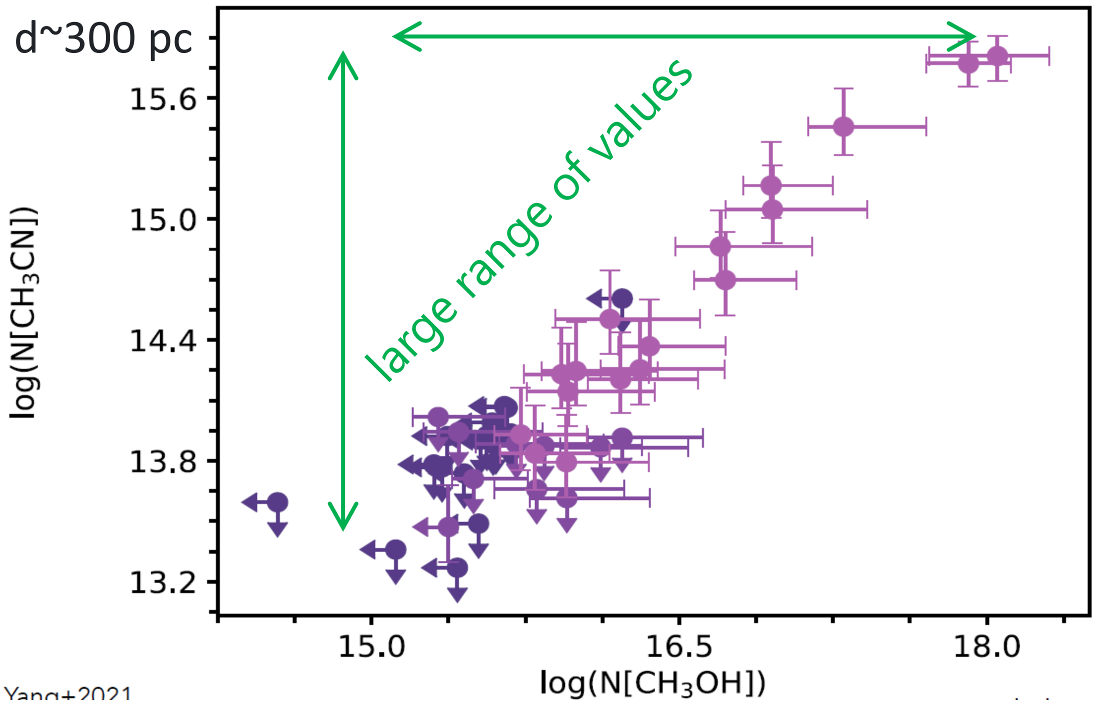
Contours: Continuum@1.3mm
0.0006, 0.003, 0.015, 0.03, 0.06 [Jy/beam]

COMs are found in 58% of the sources!

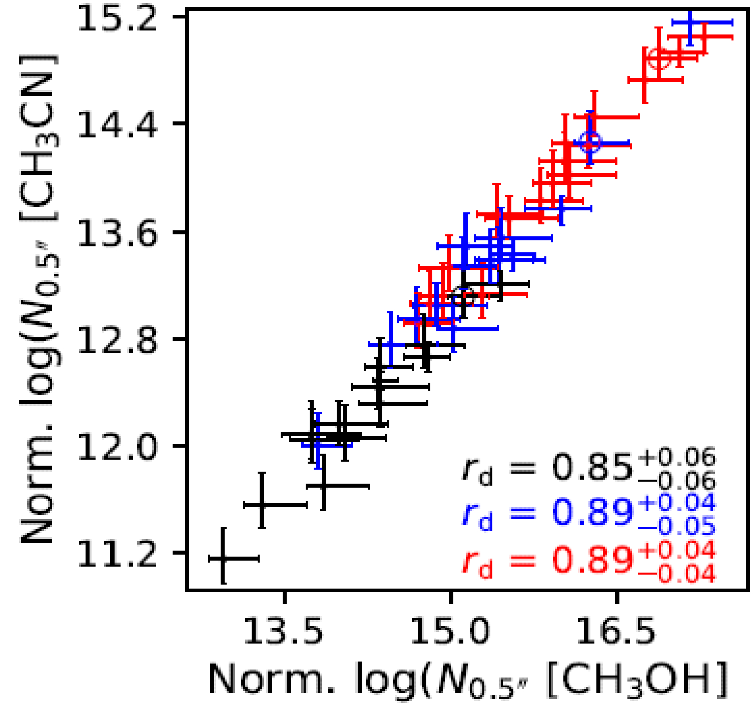
(Yang, Y-L, NS+2021, ApJ, 910, 20.)

Oxygen vs Nitrogen Chemistry

ALMA data:
PI Sakai
~50 YSOs
in Perseus
d~300 pc



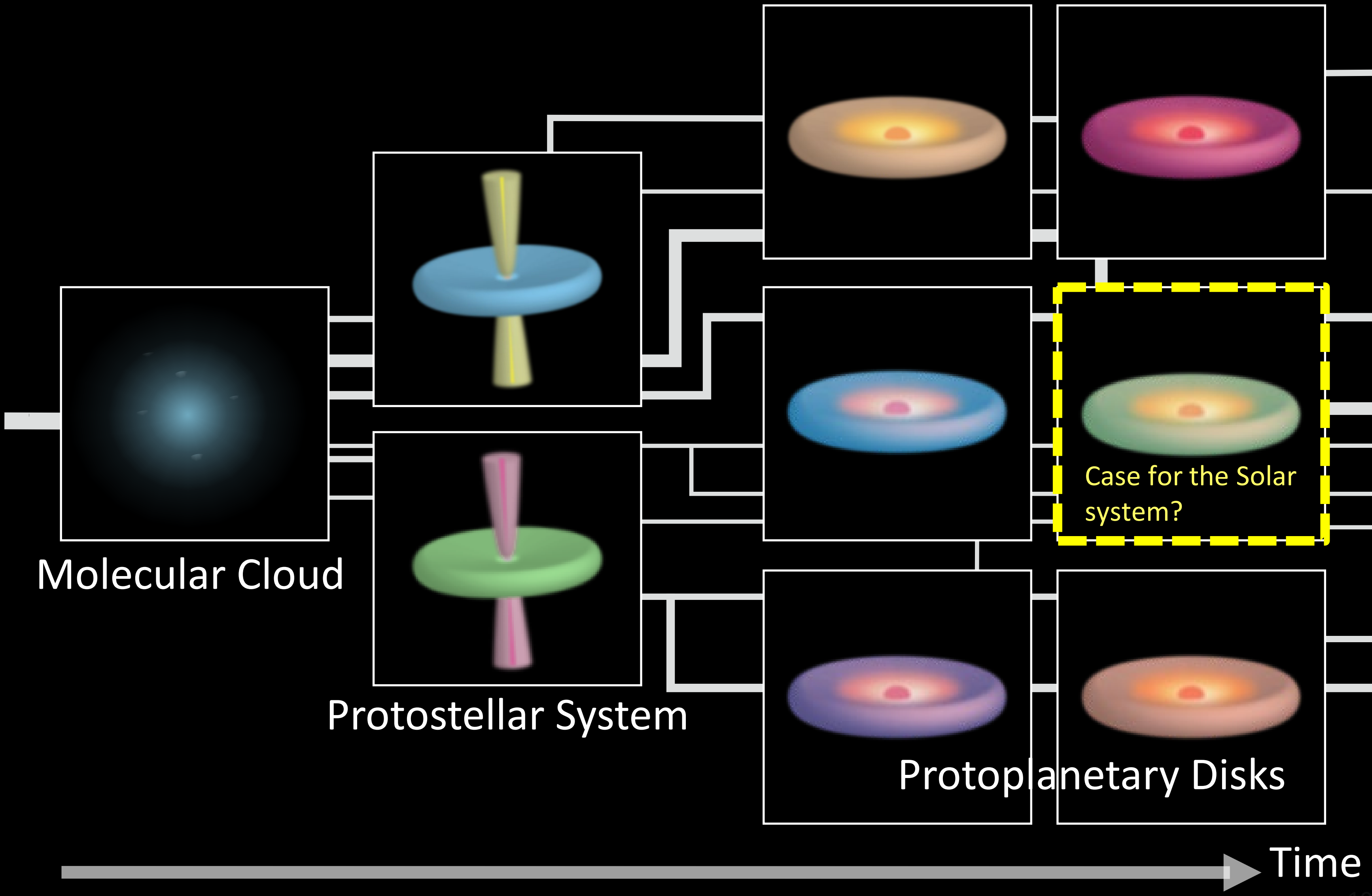
Normalized by
$T_{\rm b,cont}$, $T_{\rm b,cont}L_{\rm bol}$, $T_{\rm b,cont}T_{\rm bol}$



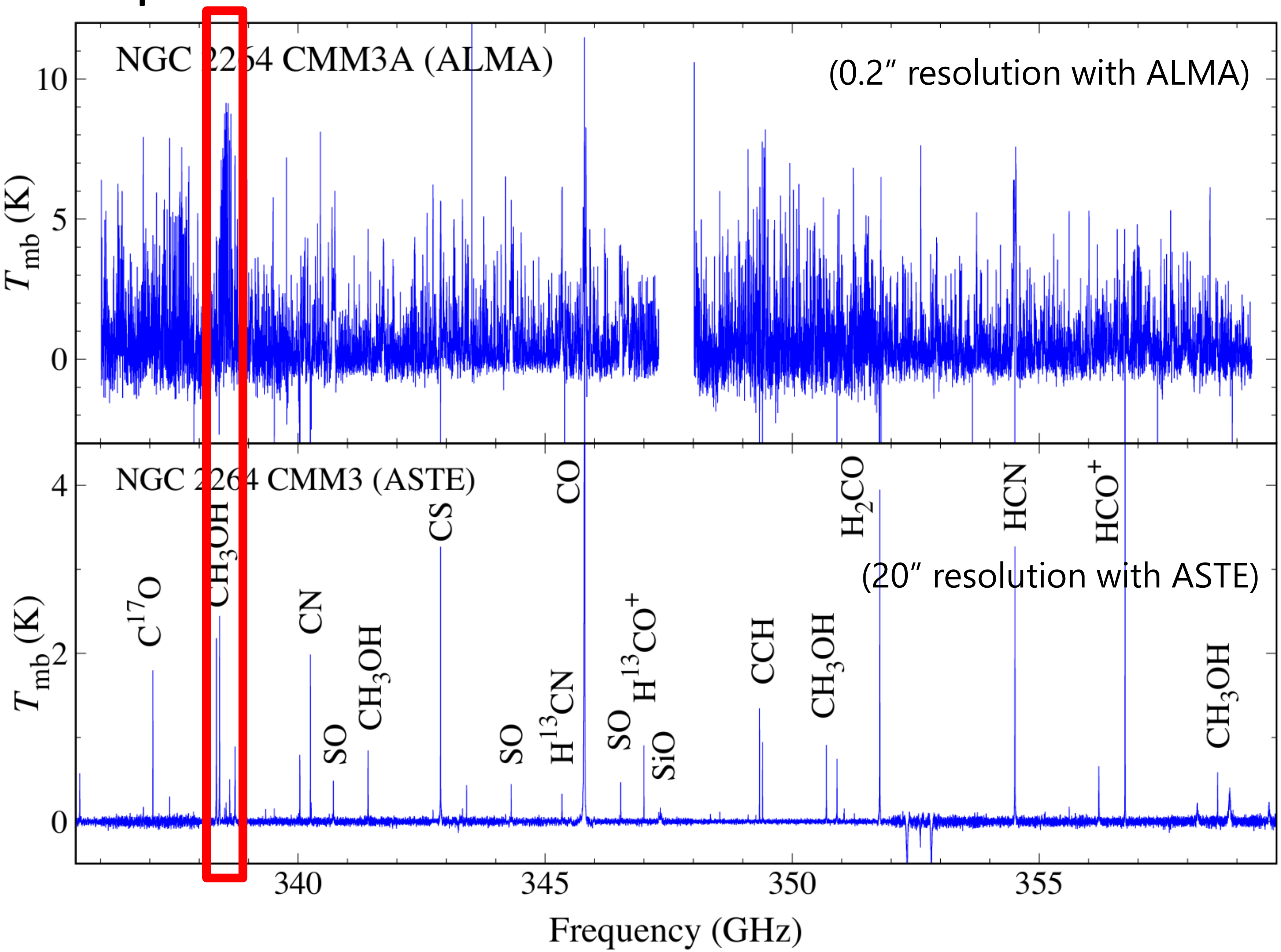
Beautiful correlation between CH_3OH and CH_3CN
Chem. relation & Large abundance range (>10^2 times).

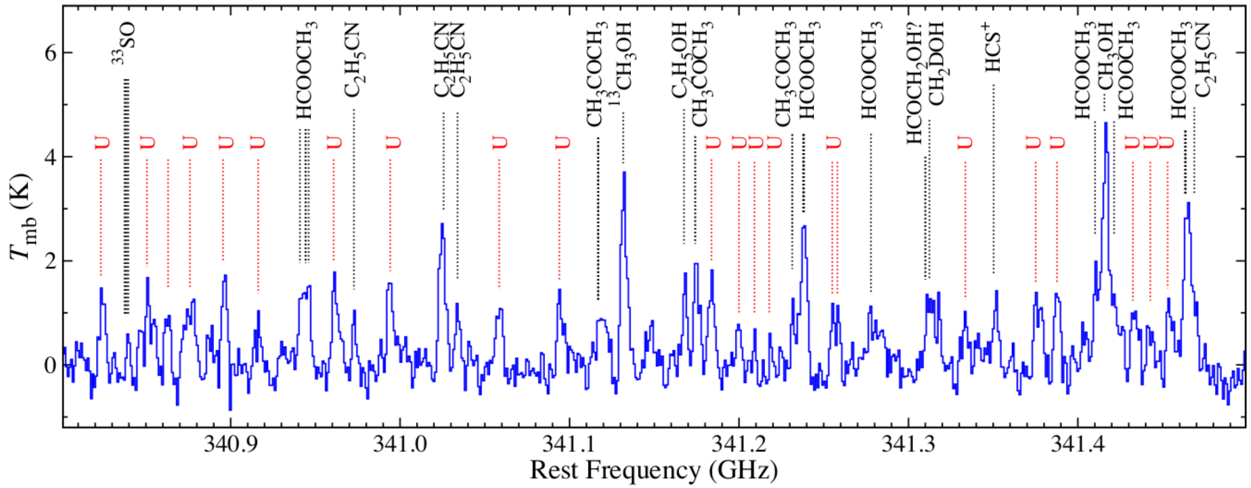
(Yang, Y-L, NS+2021, ApJ, 910, 20.)

Locate our Solar system in the diversity

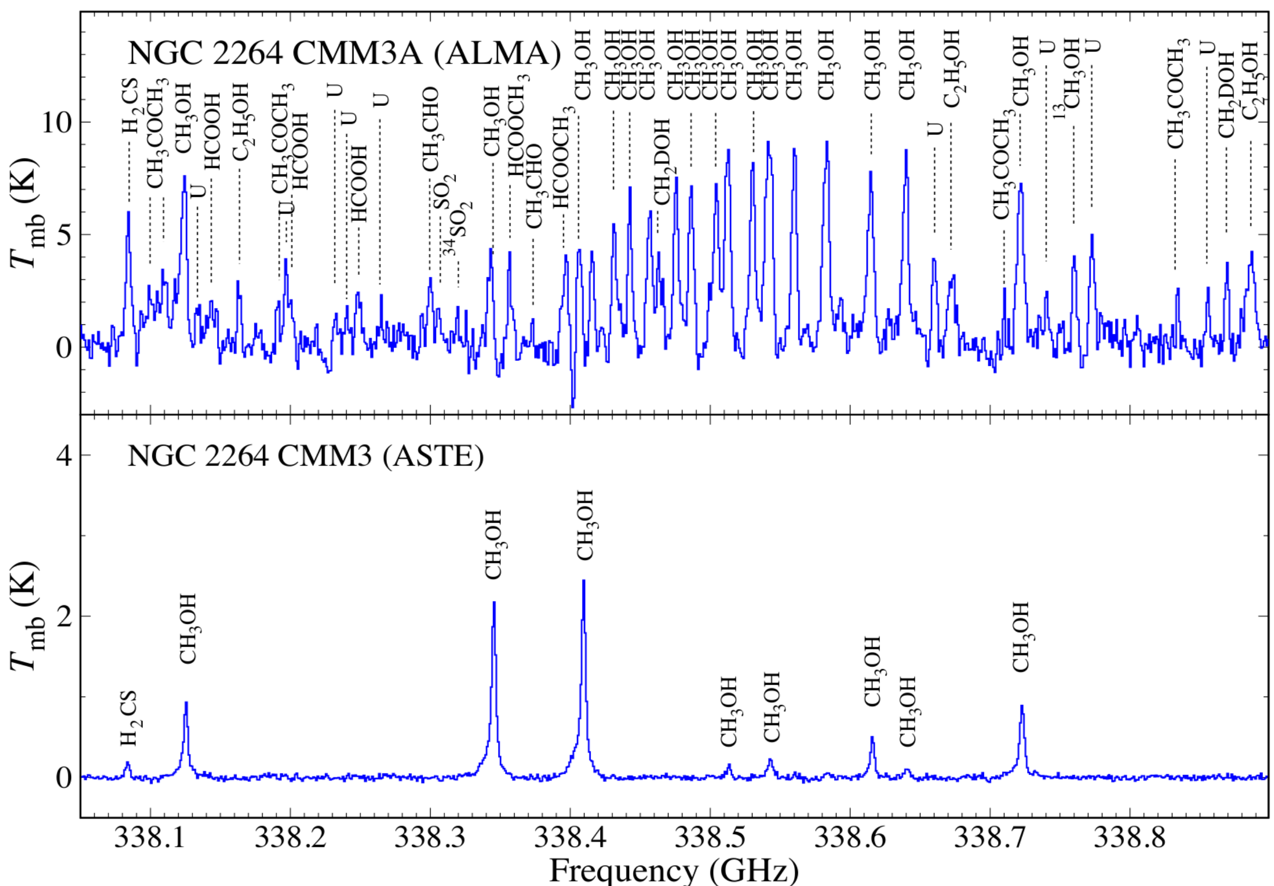


Spectrum taken toward NGC2264CMM3A



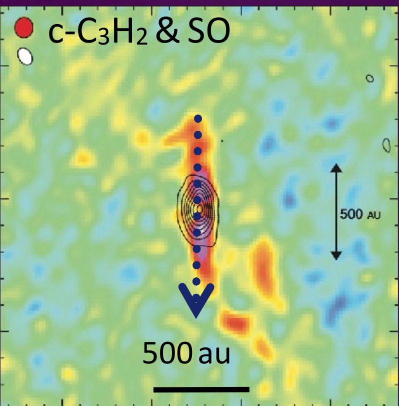


T_{mb} (K)
Rest Frequency (GHz)
340.9
341.0
341.1
341.2
341.3
341.4
0
2
4
6
U
^{33}SO
$HCOOCH_3$
C_2H_5CN
CH_3COCH_3
$^{13}CH_3OH$
C_2H_5OH
HCOCH$_2$OH?
CH_2DOH
HCS^+
CH_3OH

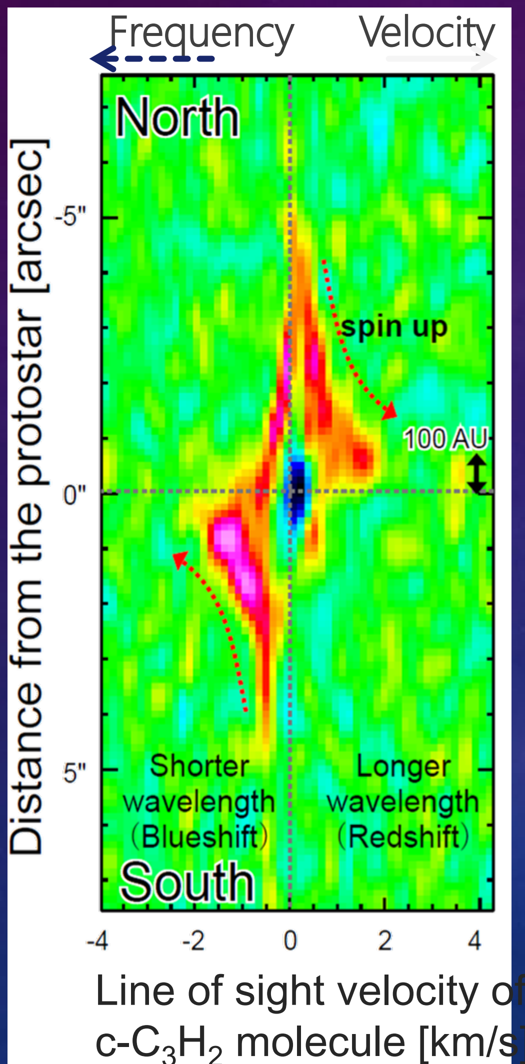


NGC 2264 CMM3A (ALMA)
NGC 2264 CMM3 (ASTE)
T_{mb} (K)
Frequency (GHz)
338.1
338.2
338.3
338.4
338.5
338.6
338.7
338.8
0
5
10
2
4
H_2CS
CH_3COCH_3
CH_3OH
U
HCOOH
C_2H_5OH
CH_3CHO
SO_2
$^{34}SO_2$
$HCOOCH_3$
CH_2DOH
$^{13}CH_3OH$

Required accuracy for Doppler analysis



Centrifugal Barrier
Sakai+ (2014)
Nature



Thermal line width ~ 0.1 km/s

→<<250 kHz @ 800 GHz=0.8 THz
(Various high excitation lines)
ALMA

→ <<50 kHz @ 160 GHz
(iCOMs)
ALMA/NOEMA & IRAM-30m

→ <<5 kHz @ 16 GHz
(Larger iCOMs e.g. with rings)
VLA & GBT/Yabes-40m

Infrared Thermometers ➡ **Check human body for a fever**

-Measure energy from stars

by measuring the heat energy

→Ideal for anyone who may have to worry about cross contamination such as infants.

Technology Developed for Astronomy
Meets
Molecular Science ?

Heterodyne Radio-Receiver ➡ **Intensity Measurement of Lines from Molecules**

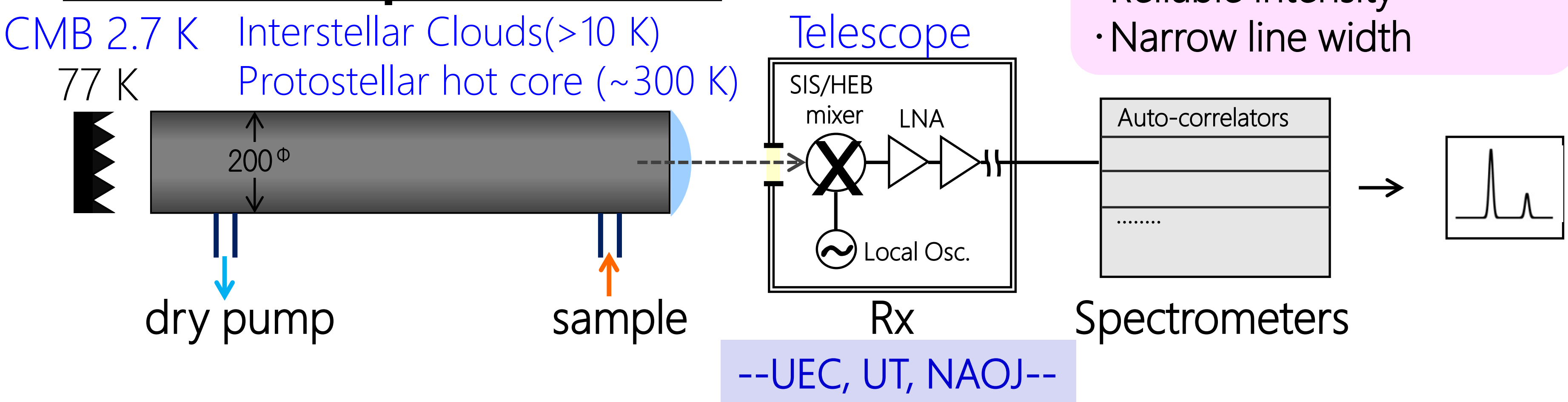
-Observe molecules in space

Determine temperature and abundance without direct interaction with the gas.

Observing Gas Cell instead of the Sky

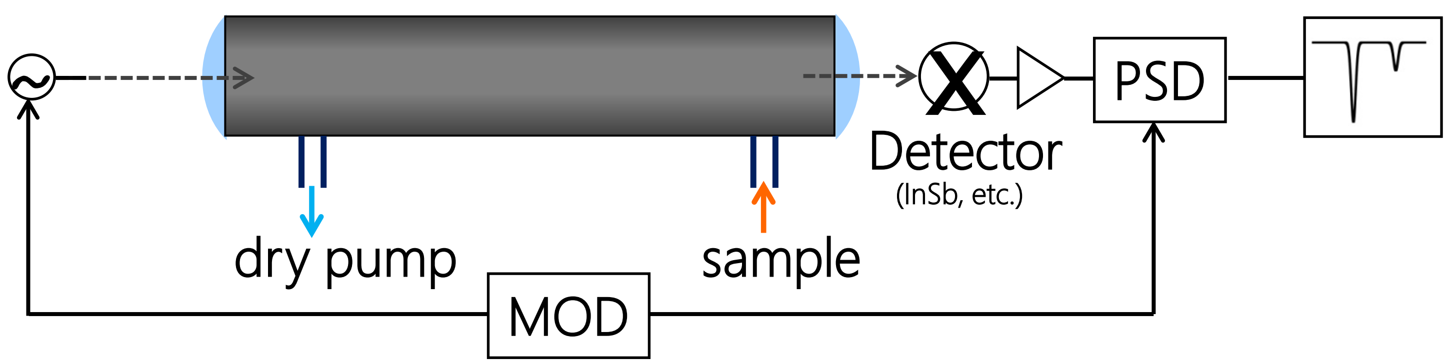
Emission Spectrometer

- Wide frequency coverage
- Reliable intensity
- Narrow line width



Disadvantage: low sensitivity for 1 line detection

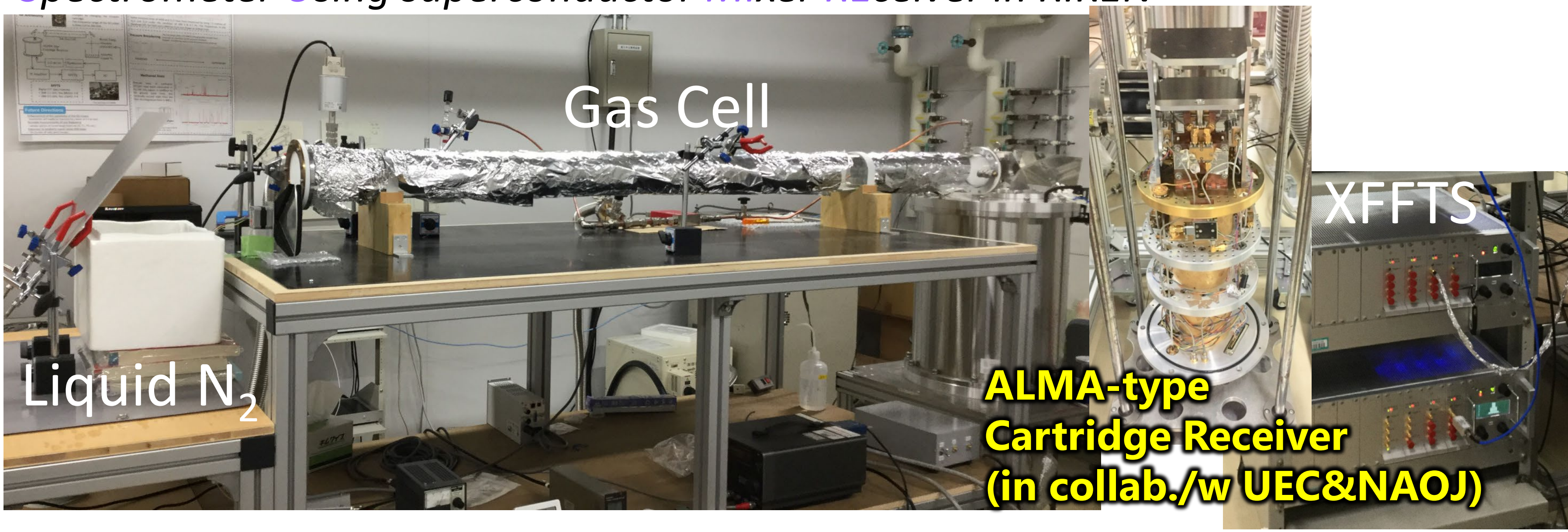
Conventional Absorption Spectrometer

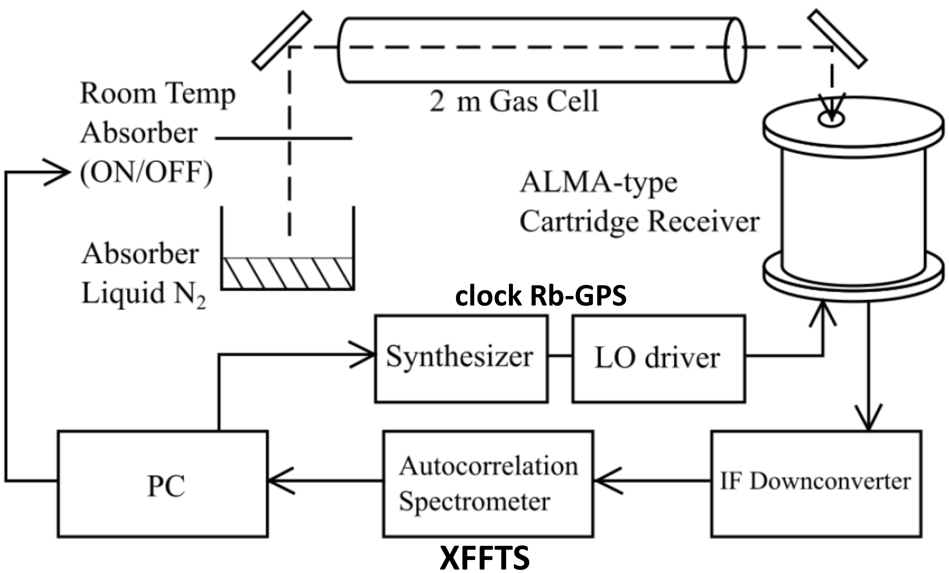


(Watanabe, Y.,,,Sakai,N+2021, PASJ, 73, 372)

SUMIRE "Observing" gas-cell instead of the sky

Spectrometer Using superconductor MIxer REceiver in RIKEN





Receivers

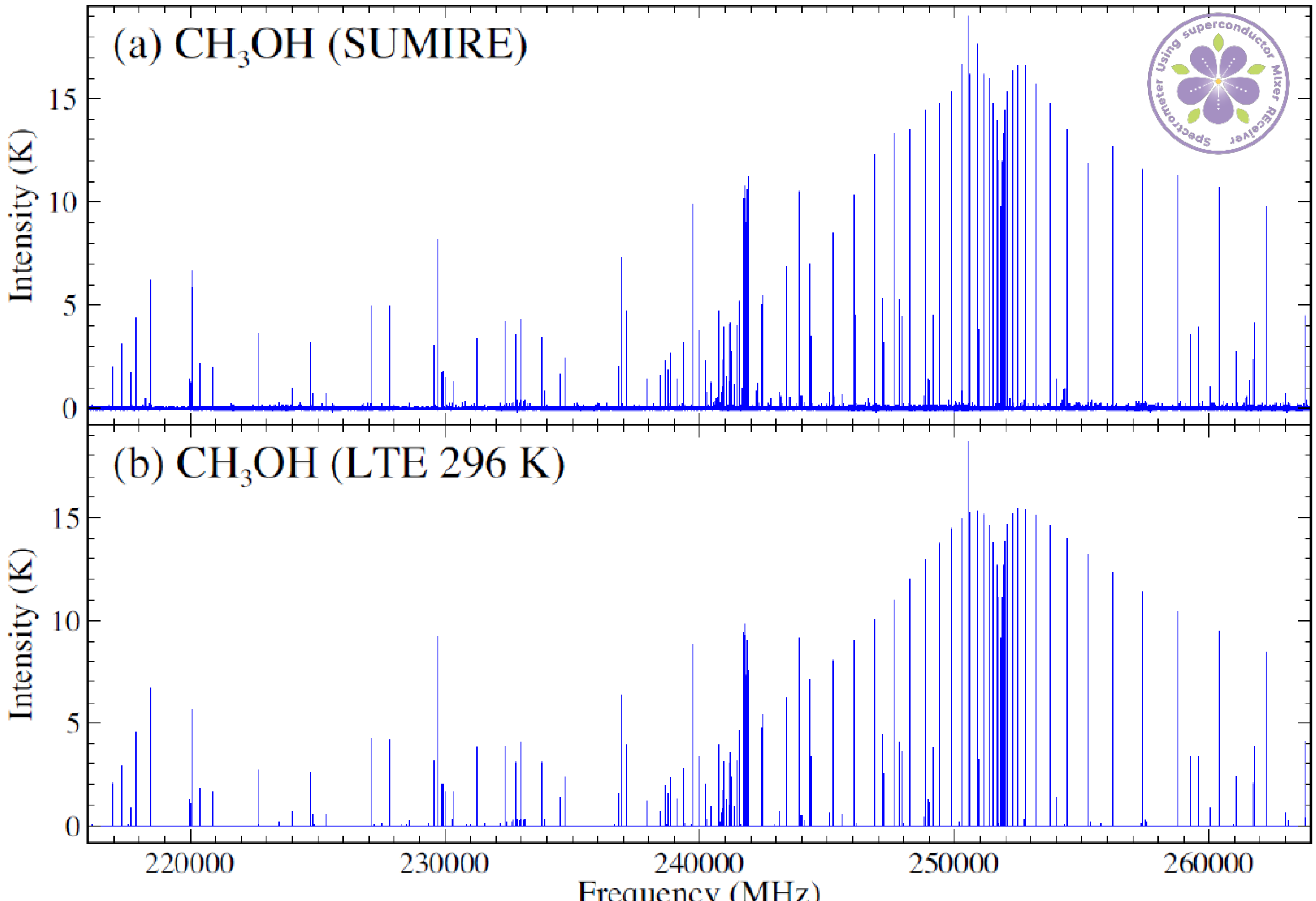
- 215-265 GHz band (ALMA-B6, SIS)
- 270-500 GHz band (ALMA-B7+8, SIS)

Freq. accuracy: ~ 1 kHz

Int. accuracy: 5-10%

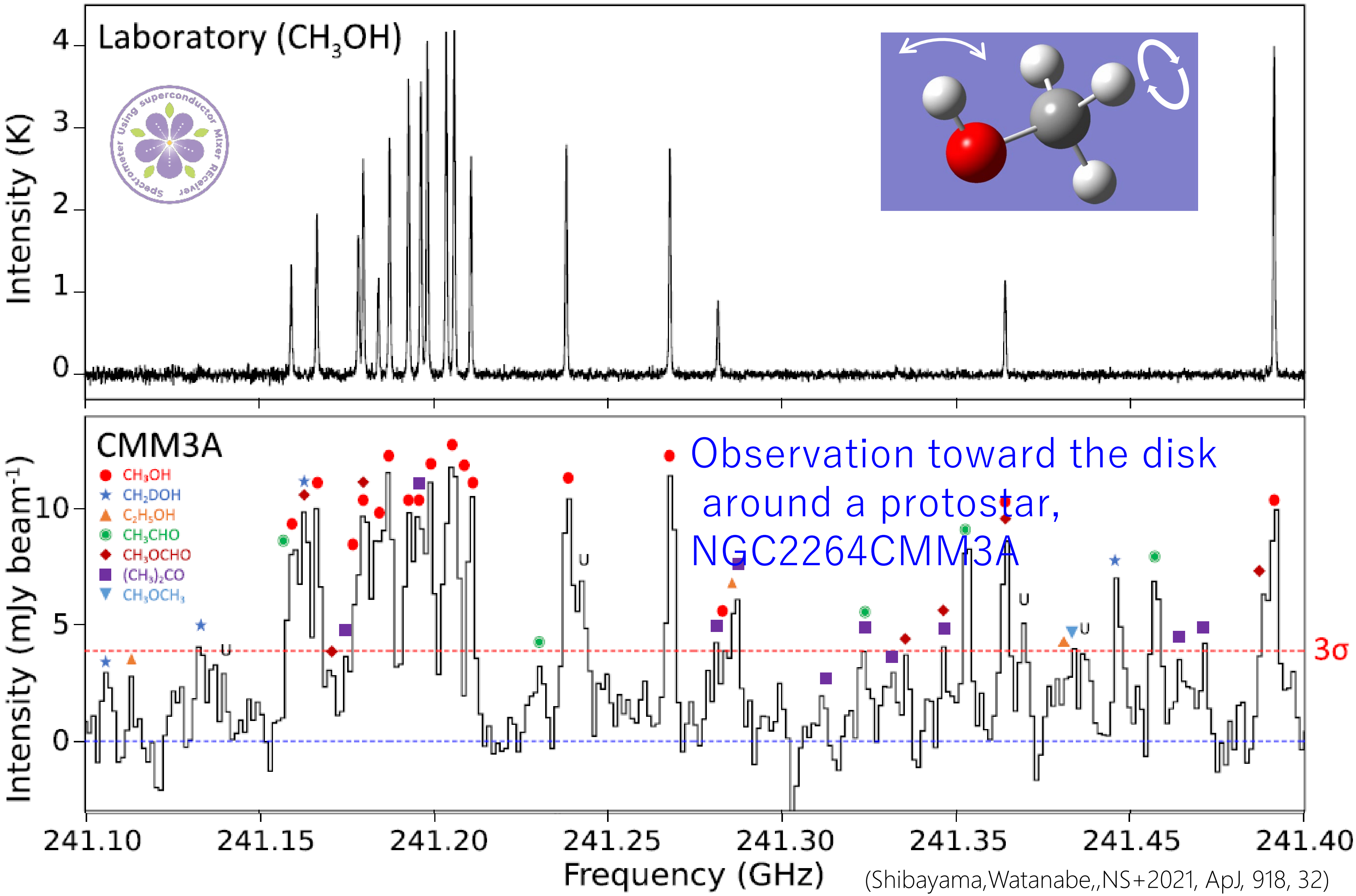
Determine
accurate frequency &
absolute intensity ($S\mu^2$)

CH_3OH Spectrum taken by SUMIRE



(Watanabe, Y., Chiba, M., Sakai,T., Tamanai, A., Suzuki, R., & Sakai, N. 2021, PASJ, 73, 372)

Origin of the "Weeds": Torsionally Excited Lines (v_t=1)

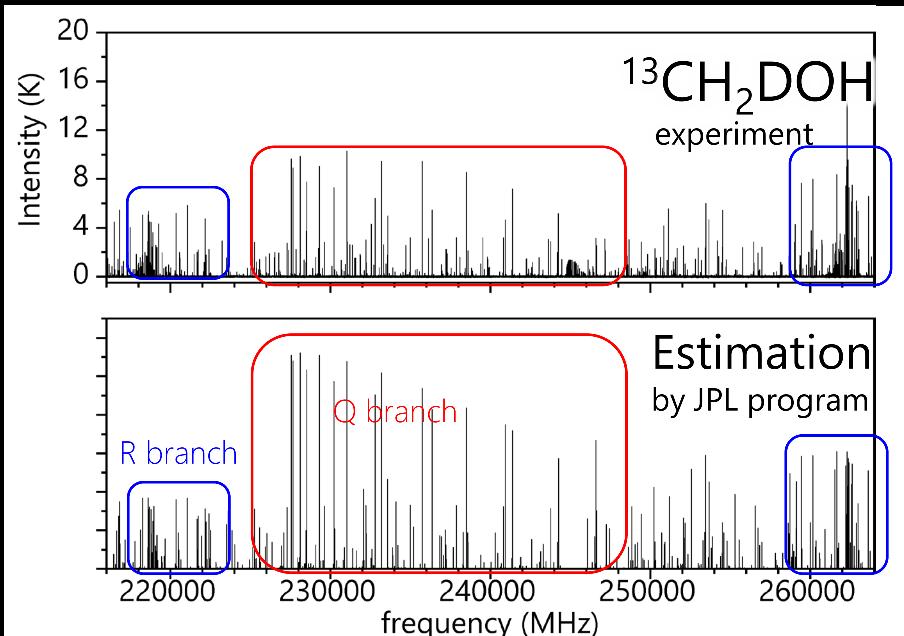


Observation toward the disk around a protostar, NGC2264CMM3A

(Shibayama, Watanabe,, NS+2021, ApJ, 918, 32)

Intensity-Calibrated Spectroscopy

SUMIRE



(Ohno, Y., Oyama, T., ,NS+2022, ApJ, 932, 101)

In JPL(NASA) web site

The intensites were calculated with the first order Fourier term of the dipole from normal methanol. The strongly allowed bands are reasonably well reproduced, but the weeker ones are not as well re-produced. Extreme caution should be used in determining columns (or concentrations) directly from b-type and c-type transitions as significant errors can occur. The a-type transitions should be much more reliable for column determinations.

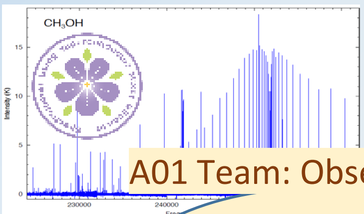
RIKEN-Pioneering Project
「**r-EMU**: Evolution of Matter in the Universe」

r-EMU Team: Nucleus

r-EMU Team: Atoms

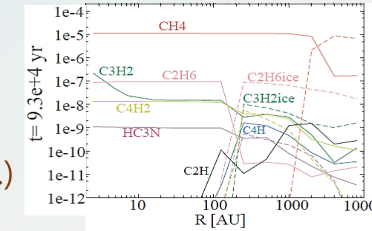
r-EMU Team: Molecules

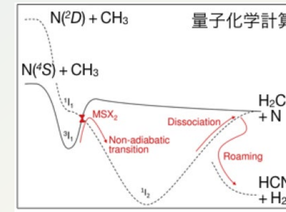
THz, Excitation Analysis, Dust evolution



Cosmic ray ionization
Isotope/Element Ratios
Energetic events
Evolved stars/Dying stars

Quantum chemical calc.
Takayanagi (Saitama-Univ.)
Yamasaki (Hirosaki-Univ.)



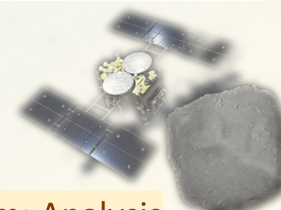


A03 Team: Theory

Chemical network calc.
Physical evolution model.
Aikawa, Y. (Univ. of Tokyo)

Models

Chemical Evolution
Physical Evolution



A01 Team: Observation

Observations

Sakai, N (RIKEN, CPR)

Spectroscopy: in collab. w. NAOJ/UEC
Observation

Distribution
Abundance
Spectroscopy

Next Generation Astrochemistry
JSPS 学術変革領域A
FY2020-2025
PI: Nami Sakai

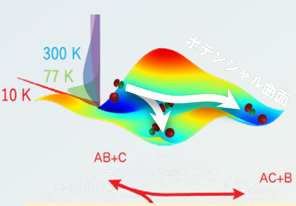
HAYABUSA 2

Mineralogy, Link to The Solar System

A02 Team: Analysis

Planetary Science

Return Samples
Tachibana, S. (Univ. of Tokyo)



Gas-Phase Reaction

Branching Ratio
Reaction Rate
Reaction Barrier

A04 Team: Gas-Phase Reaction

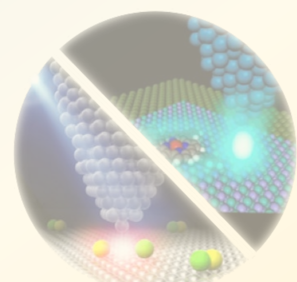
Ion - neutral-Atom: Nakano, Y. (Rikkyo Univ.)
Ion - polar-Mol.: Okada, K. (Sophia Univ.)
Ion – isomers: Tanuma, H. (Tokyo Met. Univ.)
(⇔**Neutral-Neutral:** I. Sims (Rennes1, France))

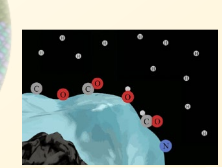
Depletion,
Desorption,
Dissociation,
Dispersion

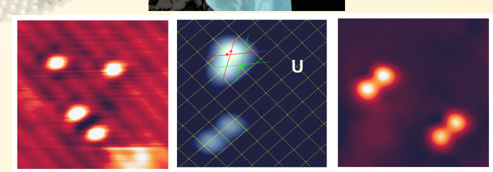
Surface Reaction

A05 Team: Surface Reaction

Micro: Imada, H., Kim, Y. (RIKEN, CPR)
Macro: Watanabe, N. (Hokkaido Univ.)







Hopping Rotation Reaction