Quest to understand the origin of the Solar system

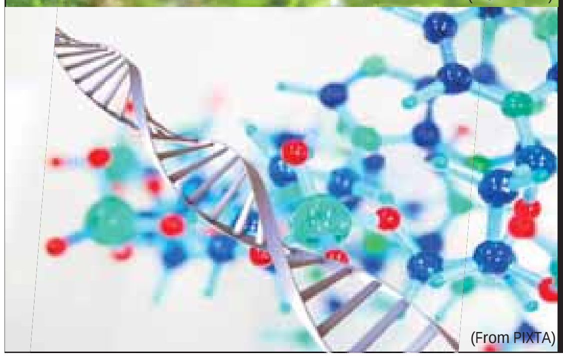
Nami Sakai (CPR, RIKEN)

Supported by

開拓研究本部 Cluster for Pioneering Research 科研費 KAKENHI JSPS

KAKENHI: Grant-in-Aid for Transformative Research Areas（A） FY2020-FY2024

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

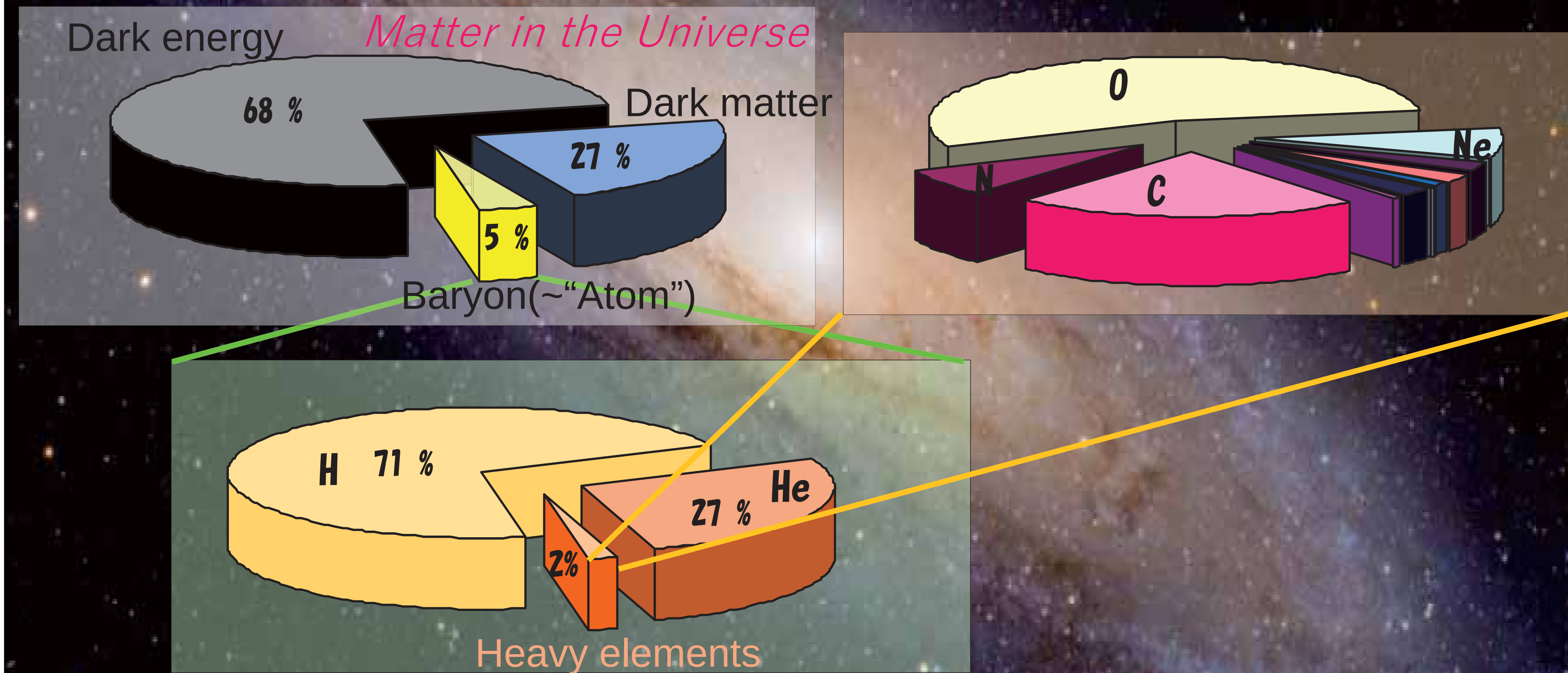


Existence of "life"
Common or Miracle?

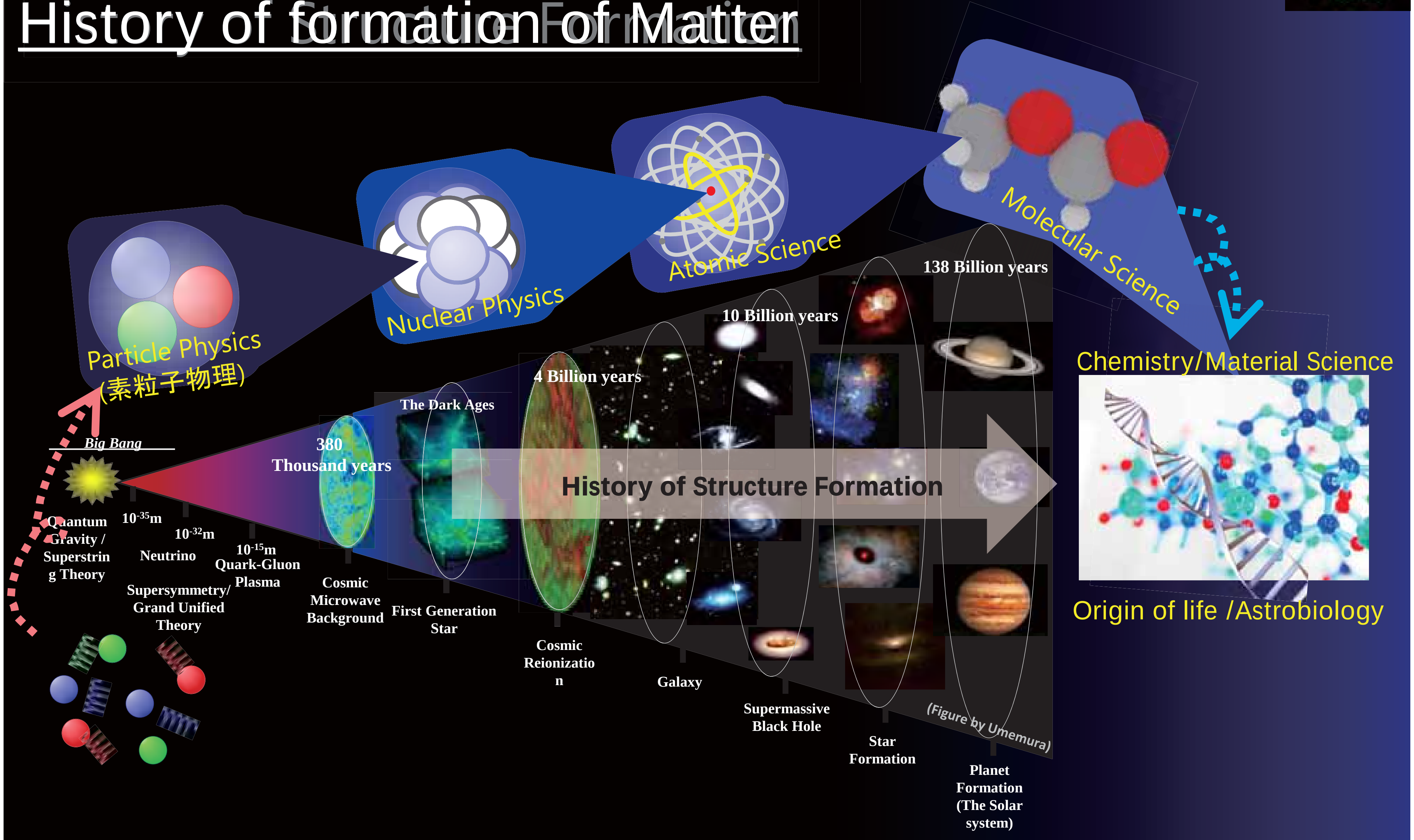
"Where do we come from?"

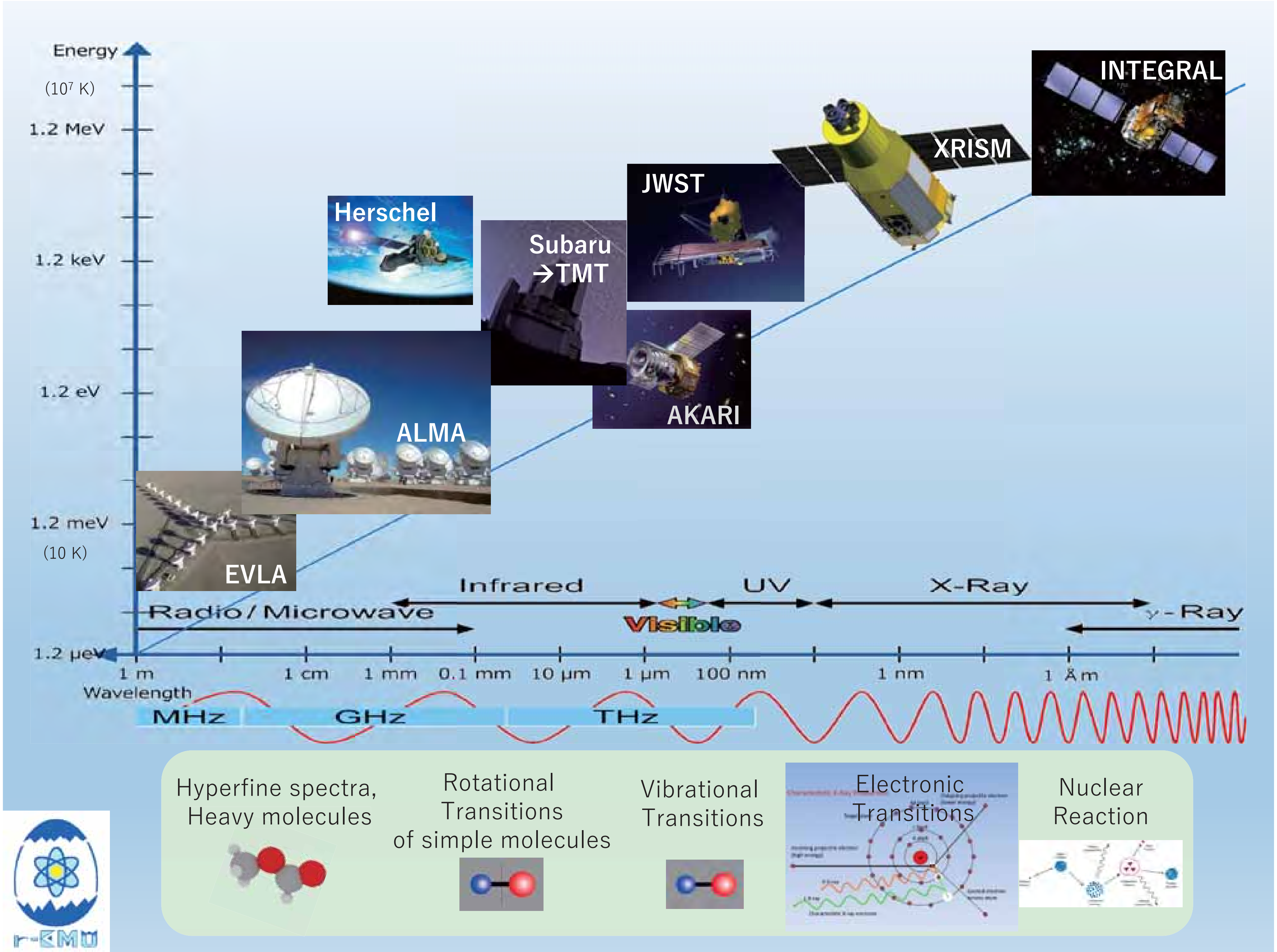
→ "How did we get here?"

Why Baryon?


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

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

Molecules in Space (~300 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, [illegible]

7 Atoms (10 Species)

C_6H, CH_2CHCN, [illegible] c-C_3HCCH, l-C_5H_2, MgC_5N, CH_2C_3N

8 Atoms (11 Species)

CH_3C_3N, HC(O)OCH_3, [illegible] $_2$CN, 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

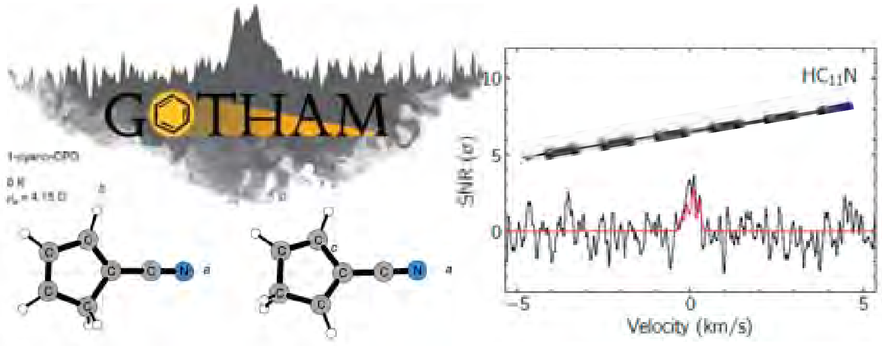
Seeking new(exotic) species in Space
Chemistry in extreme physical conditions
-"**Classical Astrochemistry**" since 1963-

Mainly detected by radio observations

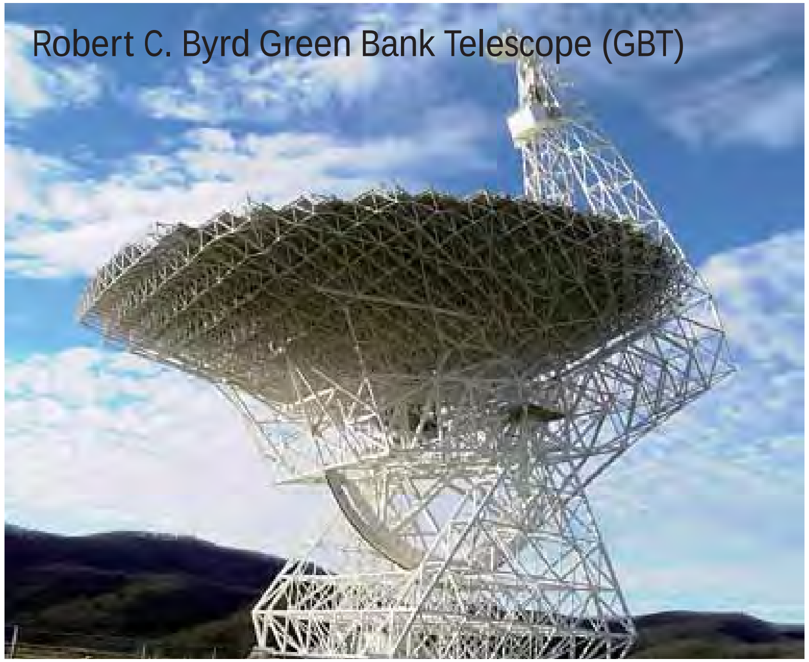
(Gray: Detected only toward AGB stars)

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

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

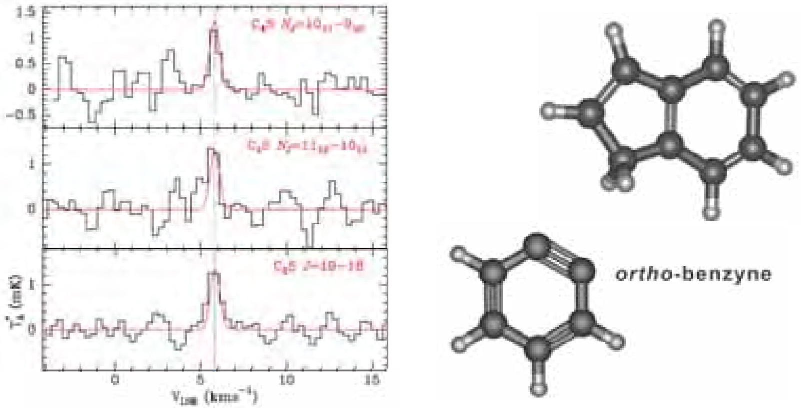


PI: Brett A. McGuire
(e.g. McGuire, B. A., et al. 2020, ApJ, 900, L10;
McCarthy, M. C., et al. 2021, Natur., 5, 176
Loomis, R. A., et al. 2021, Natur. Astro., 5, 188)



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

Molecules in Space (~300 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, ... SO_2, c-SiC_2,
CO_2, NH_2, H_3^+, ... CaNC, NCS

4 Atoms (27 Species)

c-C_3H, l-C_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)...
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

Seeking new(exotic) species in Space
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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, $C_2H_3NH_2$, $(CHOH)_2$

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H_2CCCHC...

10 Atoms (5 Species)

CH_3C_5N, $(CH_3)_2CO$, ... (?), HC_7NH^+

11 Atoms (4 Species)

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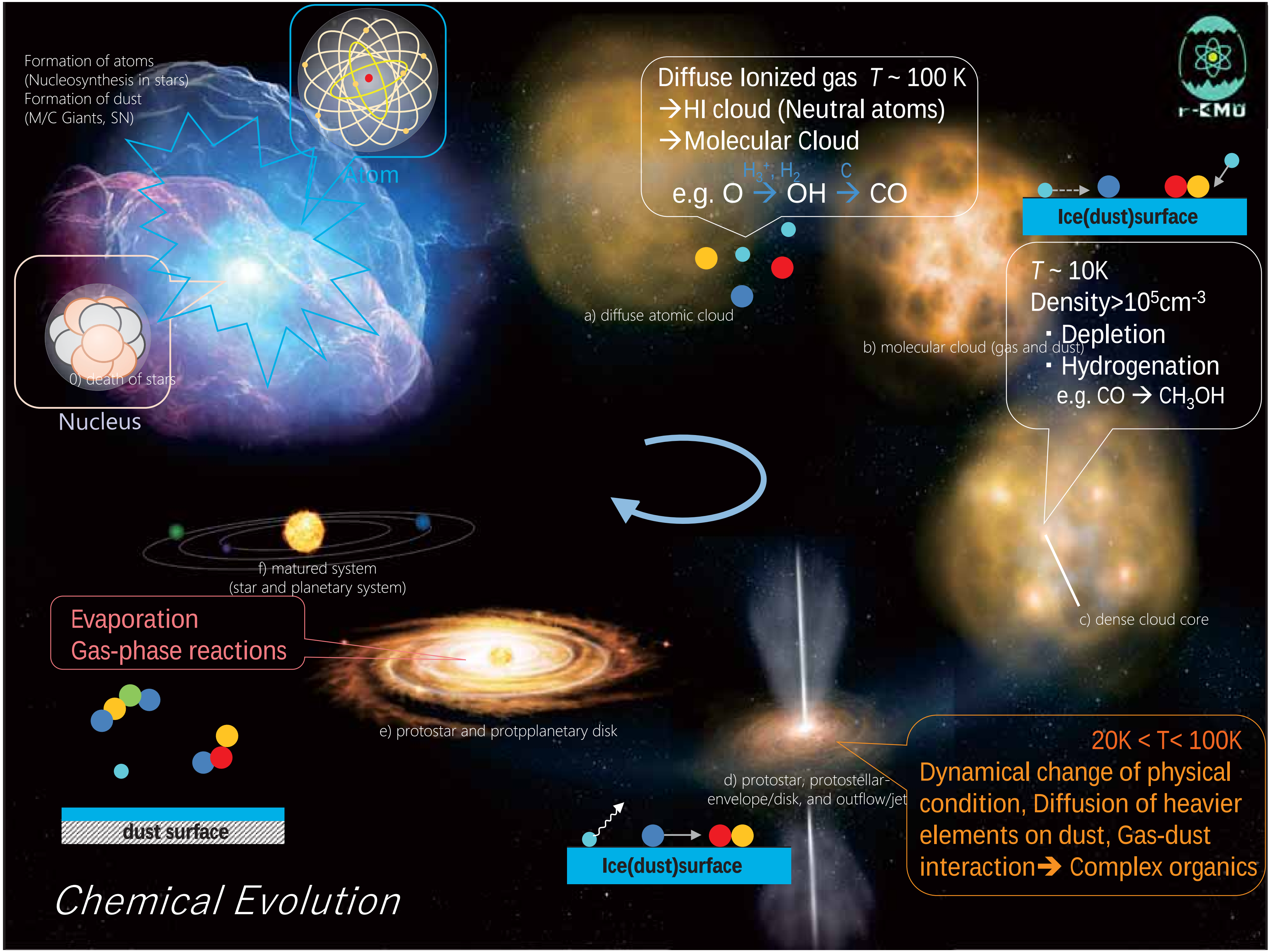
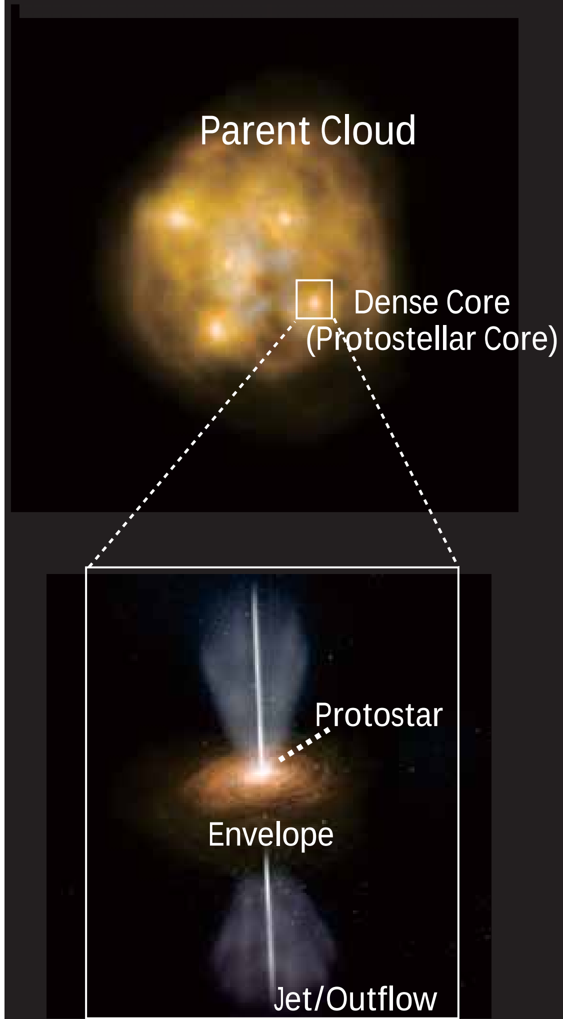
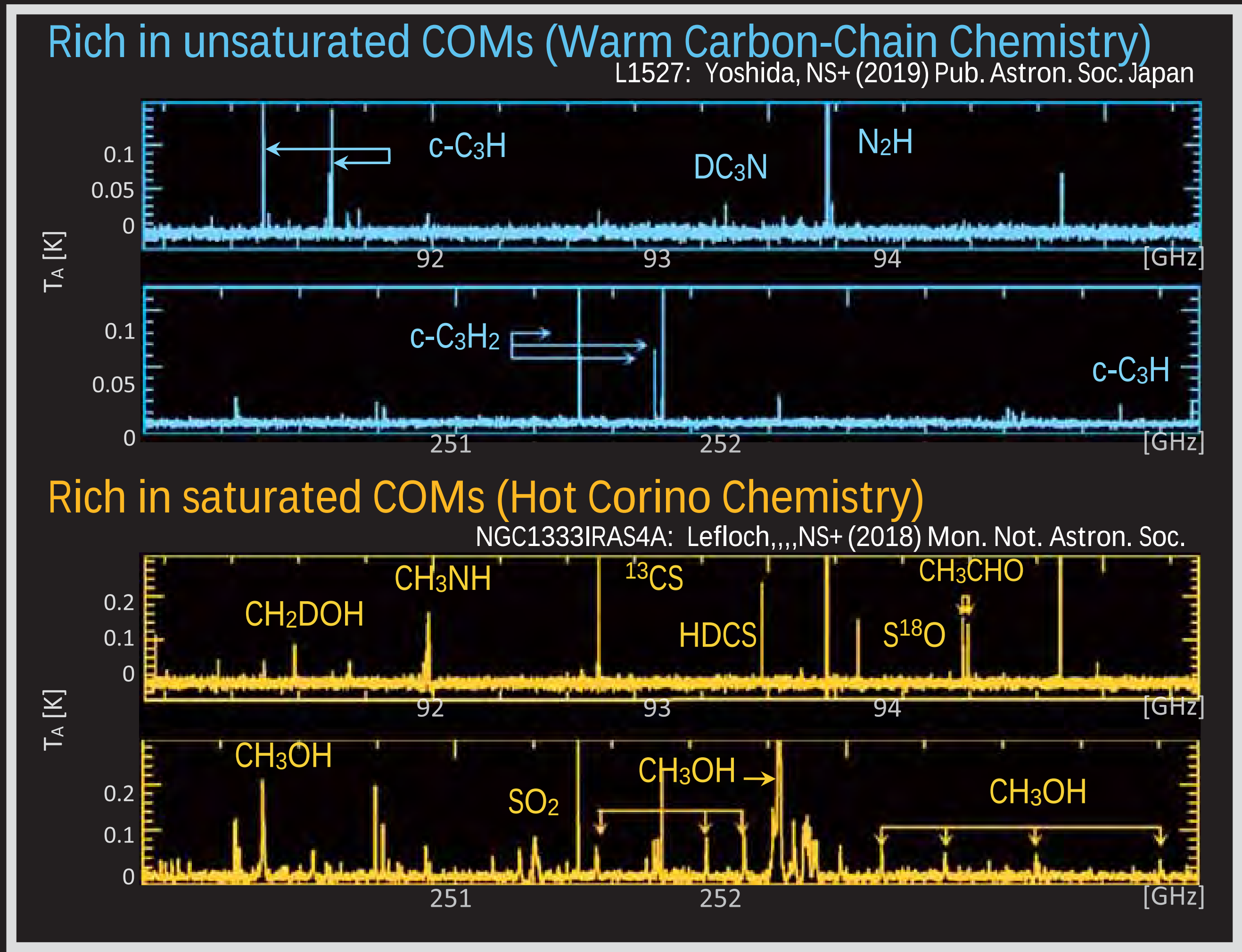
How they formed along star formation?
How they delivered to planets?
Any relation to the birth of life?

Mainly detected by radio observations
(Gray: Detected only toward AGB stars)
(The Cologne Database for Molecular Spectroscopy (CDMS): June. 2022)


Formation of atoms
(Nucleosynthesis in stars)
Formation of dust
(M/C Giants, SN)
Atom
0) death of stars
Nucleus
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
b) molecular cloud (gas and dust)
Ice(dust)surface
T ~ 10K
Density>10^5cm^{-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
dust surface
d) protostar, protostellar-
envelope/disk, and outflow/jet
Ice(dust)surface
20K < T< 100K
Dynamical change of physical
condition, Diffusion of heavier
elements on dust, Gas-dust
interaction→ Complex organics
Chemical Evolution

Chemical Composition in Cloud-Core (Envelope) Scale



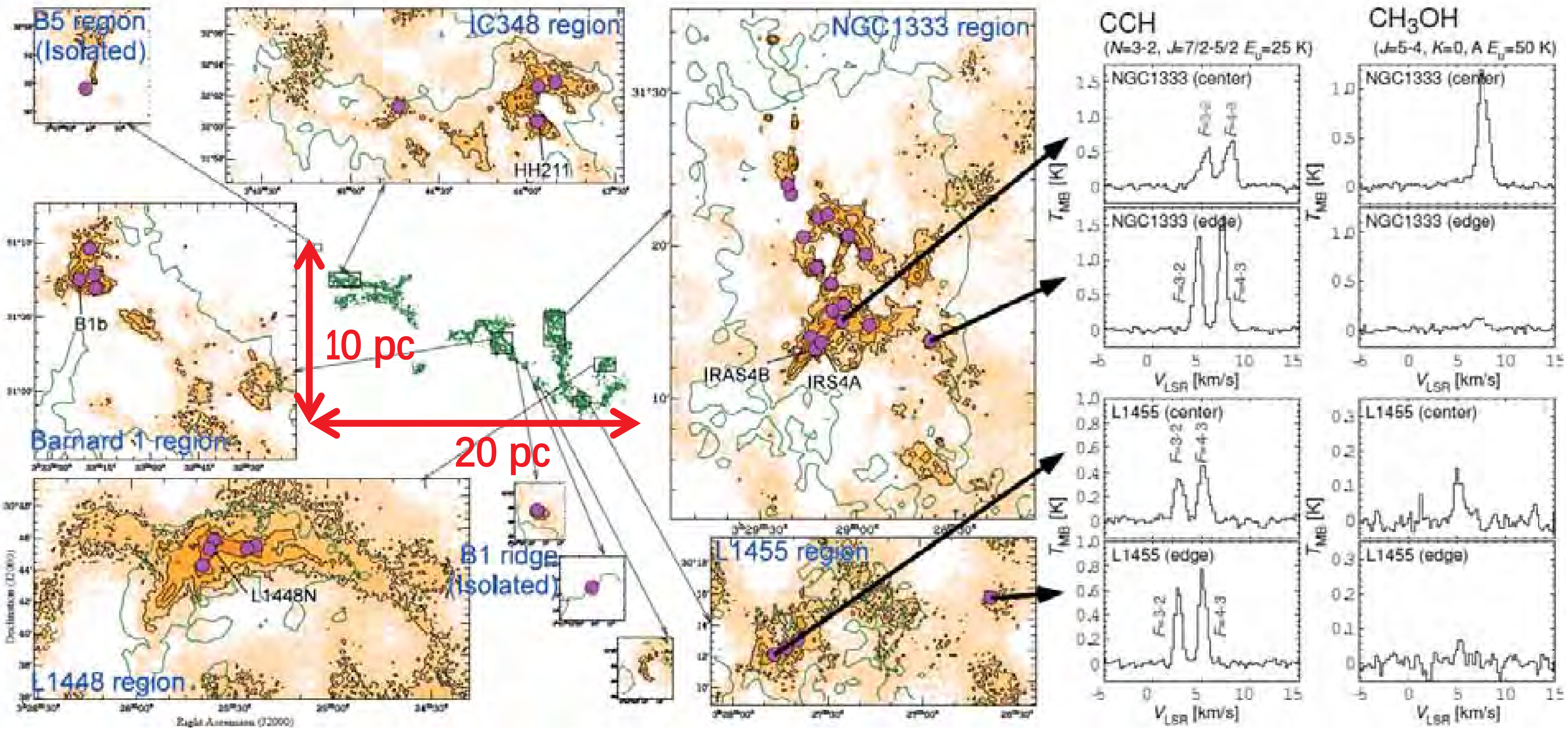


Which is the dominant case ? Which is the case for our solar system??

Perseus Chemical Survey

Exploring core (~5,000 au) scale diversity

(Nobeyama 45 m + IRAM 30 m survey toward Class0/I sources@2014-2016)



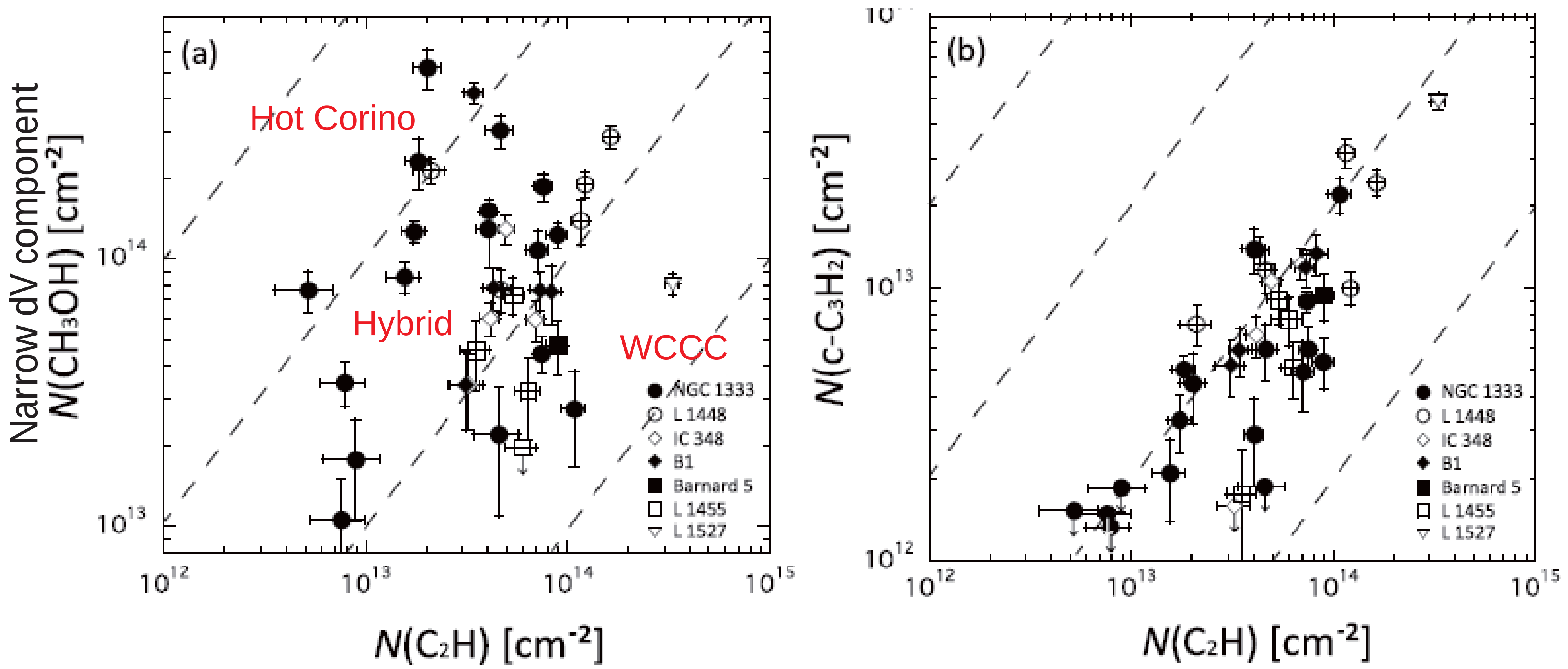
Orange: Dust, Green Contour: CO

(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)

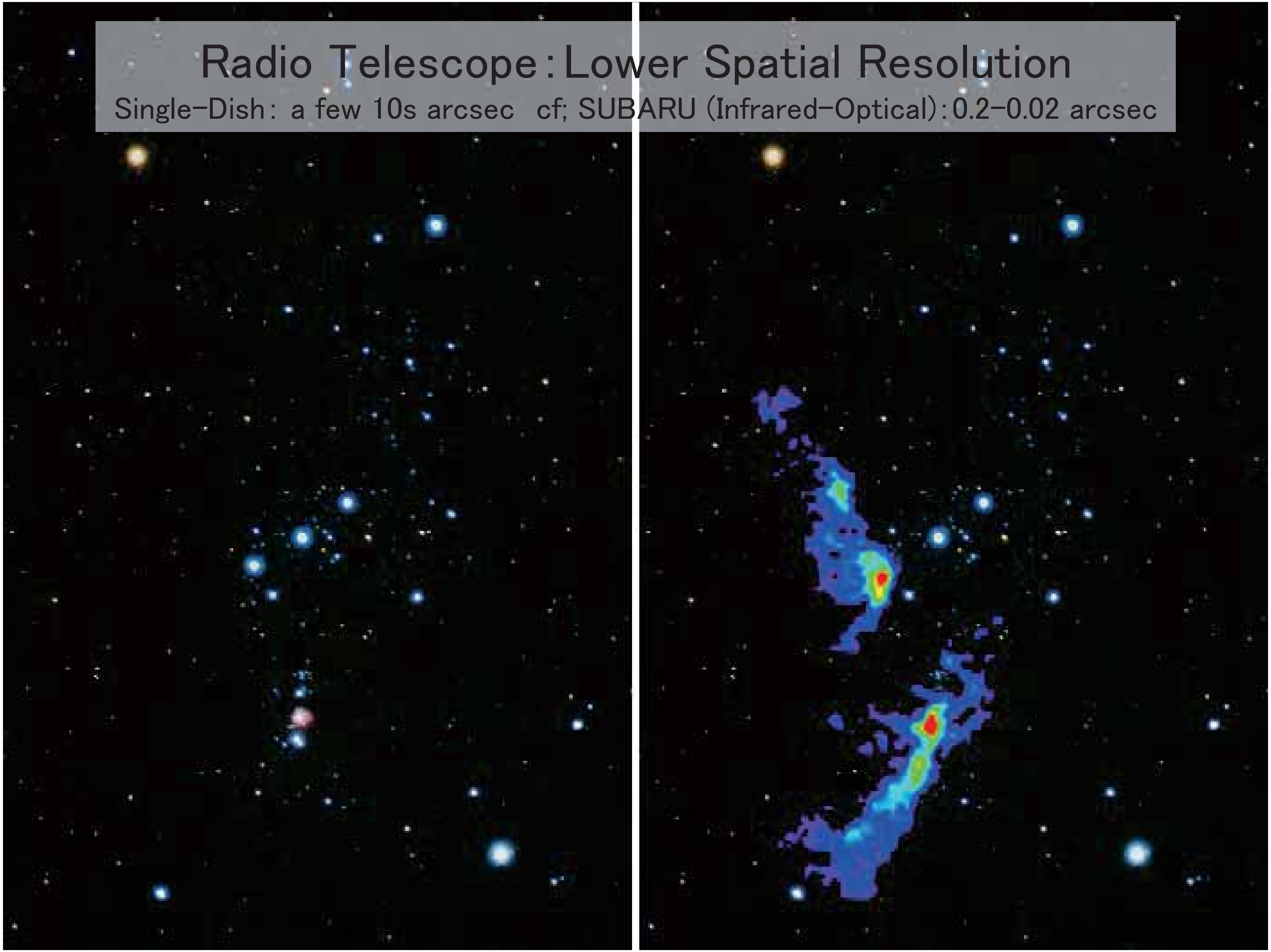


How about in protoplanetary-disk size scale ?
~100 au

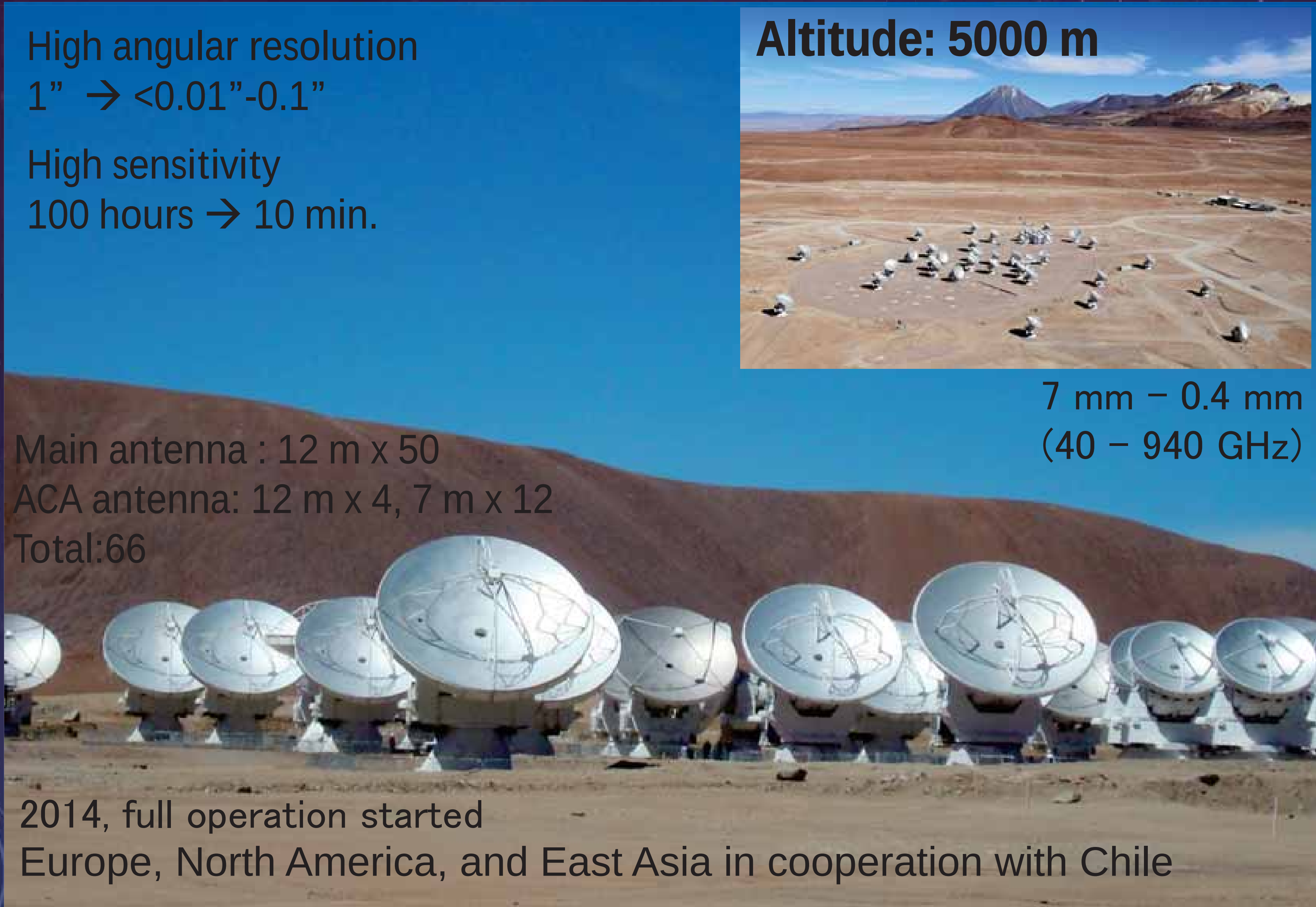
(Higuchi, NS et al. 2018, ApJS, 236, 52)

Radio Telescope：Lower Spatial Resolution

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



ALMA: Atacama Large Millimeter/sub-millimeter Array



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

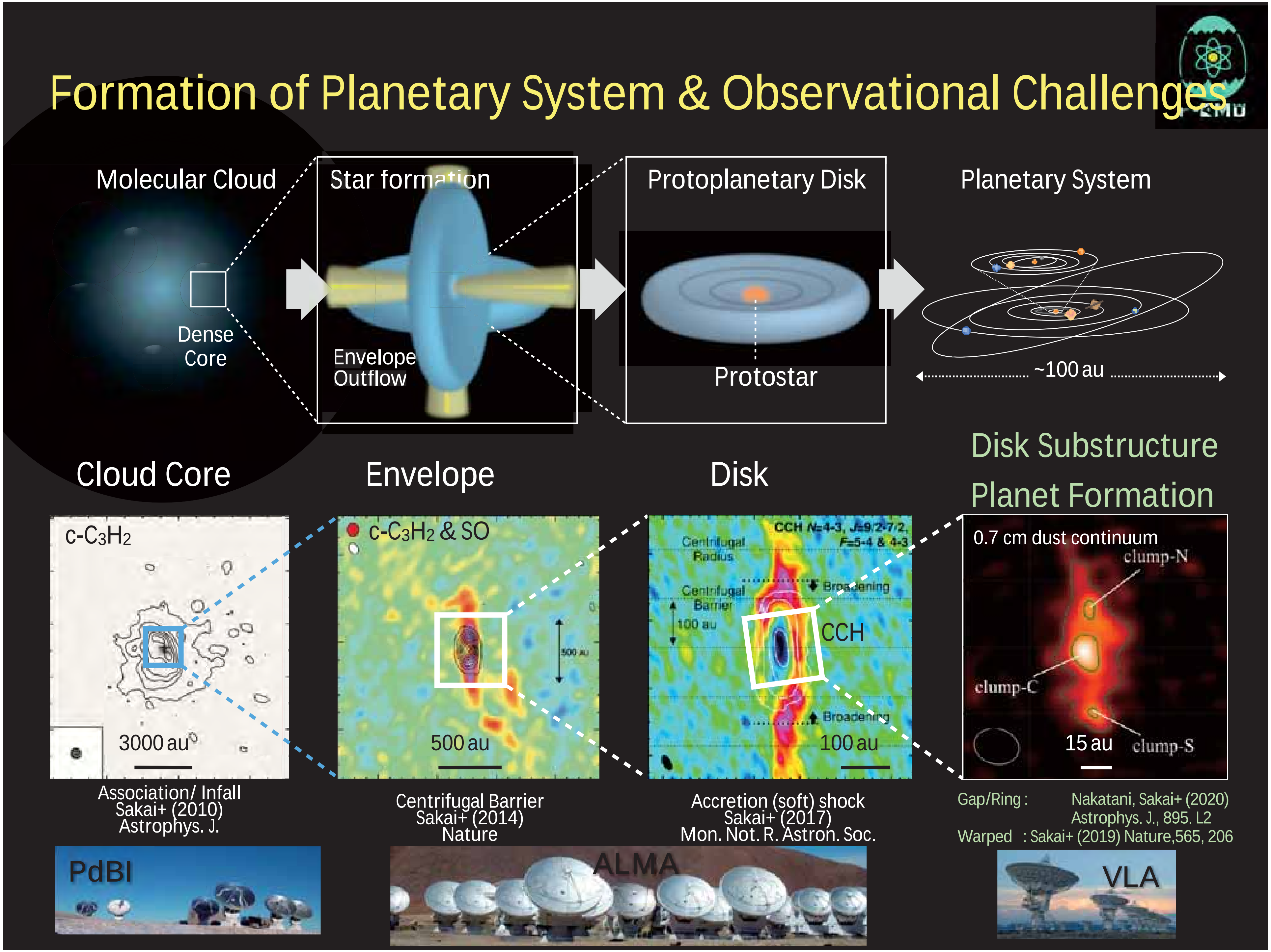
High sensitivity
100 hours → 10 min.

Altitude: 5000 m

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
Molecular Cloud
Dense Core
Star formation
Envelope
Outflow
Protoplanetary Disk
Protostar
Planetary System
~100 au
Cloud Core
Envelope
Disk
Disk Substructure
Planet Formation
c-C3H2
3000 au
c-C3H2 & SO
500 au
CCH
100 au
0.7 cm dust continuum
clump-N
clump-C
clump-S
15 au
Association/ Infall
Sakai+ (2010)
Astrophys. J.
Centrifugal Barrier
Sakai+ (2014)
Nature
Accretion (soft) shock
Sakai+ (2017)
Mon. Not. R. Astron. Soc.
Gap/Ring : Nakatani, Sakai+ (2020) Astrophys. J., 895. L2
Warped : Sakai+ (2019) Nature,565, 206
PdBI
ALMA
VLA

PErseus ALMA CHEmical Survey

PEACHES

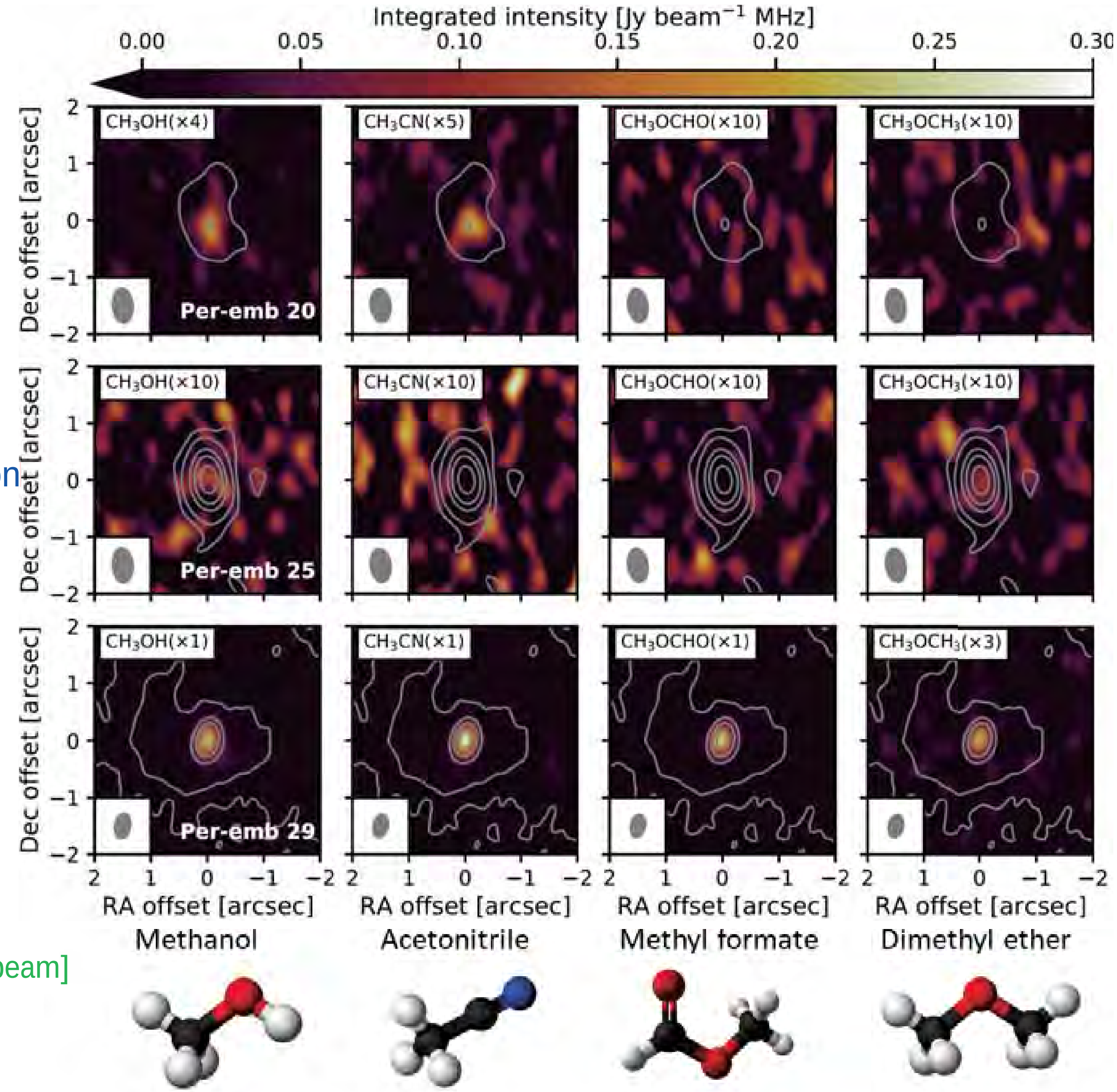
Next Generation Astrochemistry

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

Weakest cont.

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

Strongest cont.



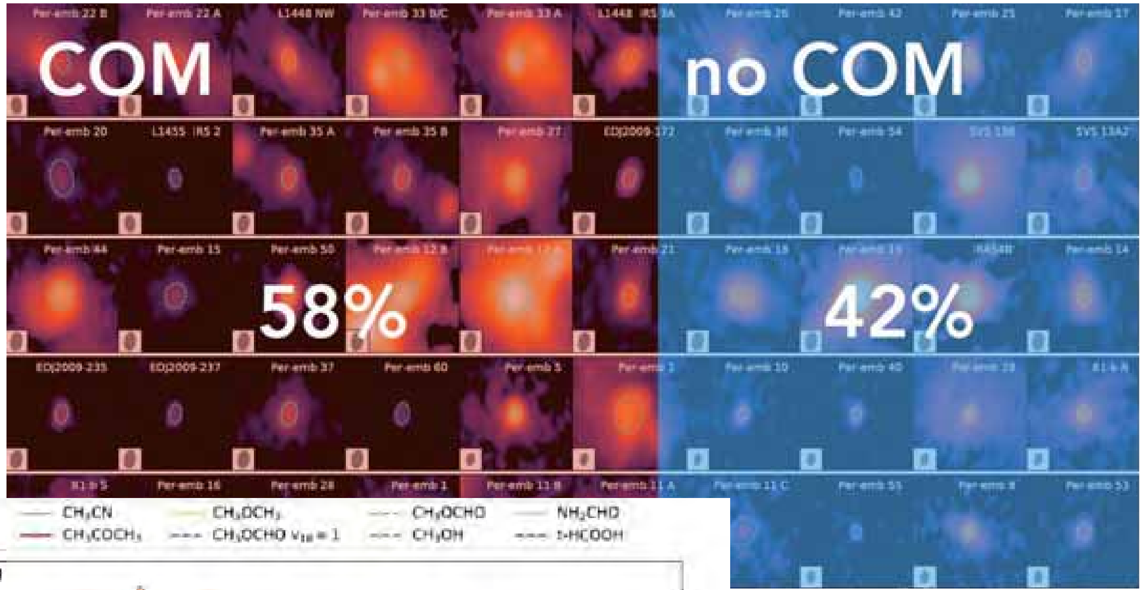
Contours: Continuum@1.3mm
0.0006, 0.003, 0.015, 0.03, 0.06 [Jy/beam]

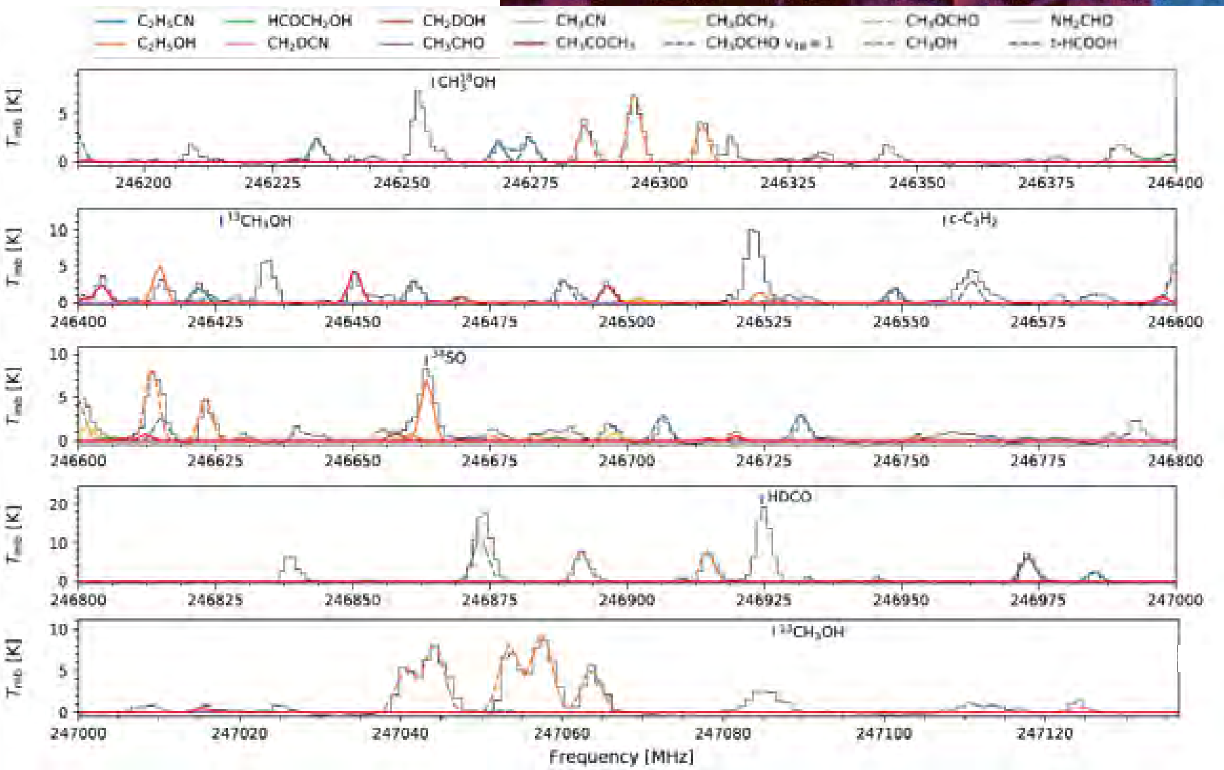
(Yang, Y-L, NS+2021, ApJ, 910, 20.)

PEACHES

PErseus ALMA CHEmical Survey

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





Zhang, Yichen
Continuum
Outflows

Yang, Yao-Lun
COMs analysis

Higuchi, Aya
Calibrations

Zeng, Shaoshan.
D/H ratios
N-bearing

Mullio, Nadia
Multiplicity
Chem.Calc

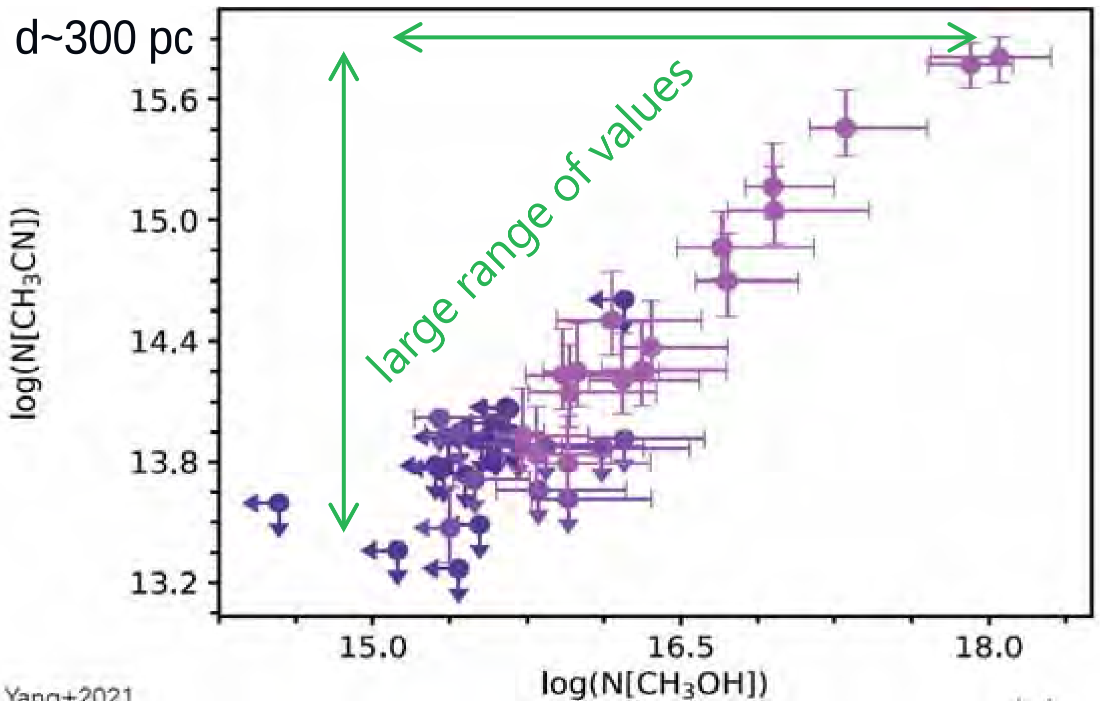
Zhang, Ziwei
SO2Excit. Calc.

Artur de la Villarmois, Elizabeth
S-bearing

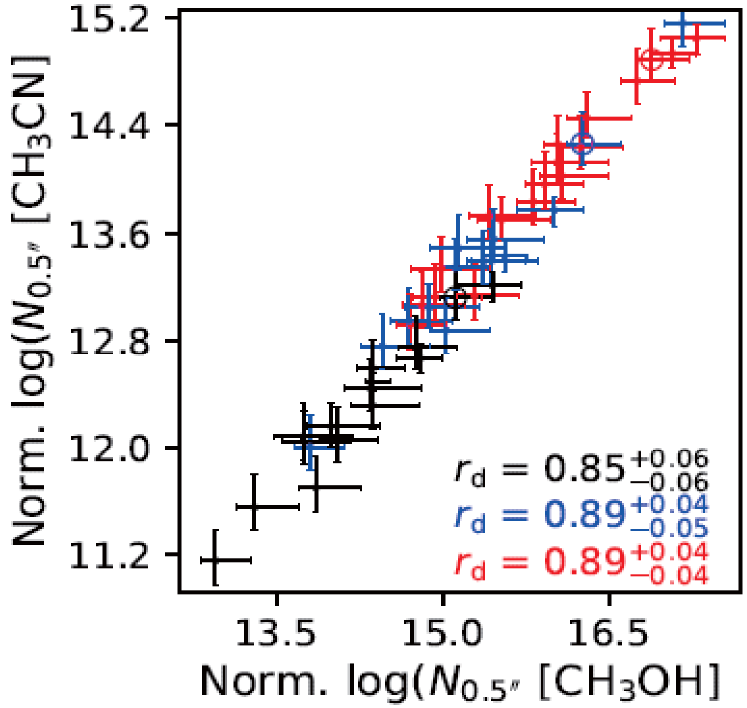
(Yang, Y-L, NS+2021, ApJ, 910, 20.)

Oxygen vs Nitrogen Chemistry

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



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



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

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

Chemistry in Gaseous Envelope/Disk

- How common is the WCCC & Hot-Corino Chemistry ?

  Semi-statistical chemical surveys in disk forming scale (100-300 au)

  PEACHES (50 YSOs in Perseus): e.g. Yang, Y.-L., Sakai+2021, *ApJ*, 910, 20

  ORANGES (19 YSOs in Orion): e.g. Bouvier, M.,,Sakai+2022, *ApJ*, 929, 10

  ALMASOP (56 YSOs in Orion): e.g. Hsu, S.-Y.,, Yang,Y.-L.+2022, *ApJ*, 927, 218

  Ophiucus (12 YSOs in Oph.): Artur de la Villarmois, E.,Sakai+2019, A&A, 626, A71

  --Diversity in disk forming region is confirmed. Regional difference is significant.

  --"Hybrid" type sources are commonly seen.

  Perseus (PEACHES) 58% /Orion (ORANGES/ALMASOP) 26-40% /Ophiuchus **0%**

- What is the origin of the diversity? (branching?)

  Large dynamic range observations vs chemical/physical models

  WCCC become active @ low T or low Av during starless phase

  Chem. network model (e.,g, Aikawa,Y.,,NS+2020, ApJ, 897, 110)

- Any other axis on chemical diversity?

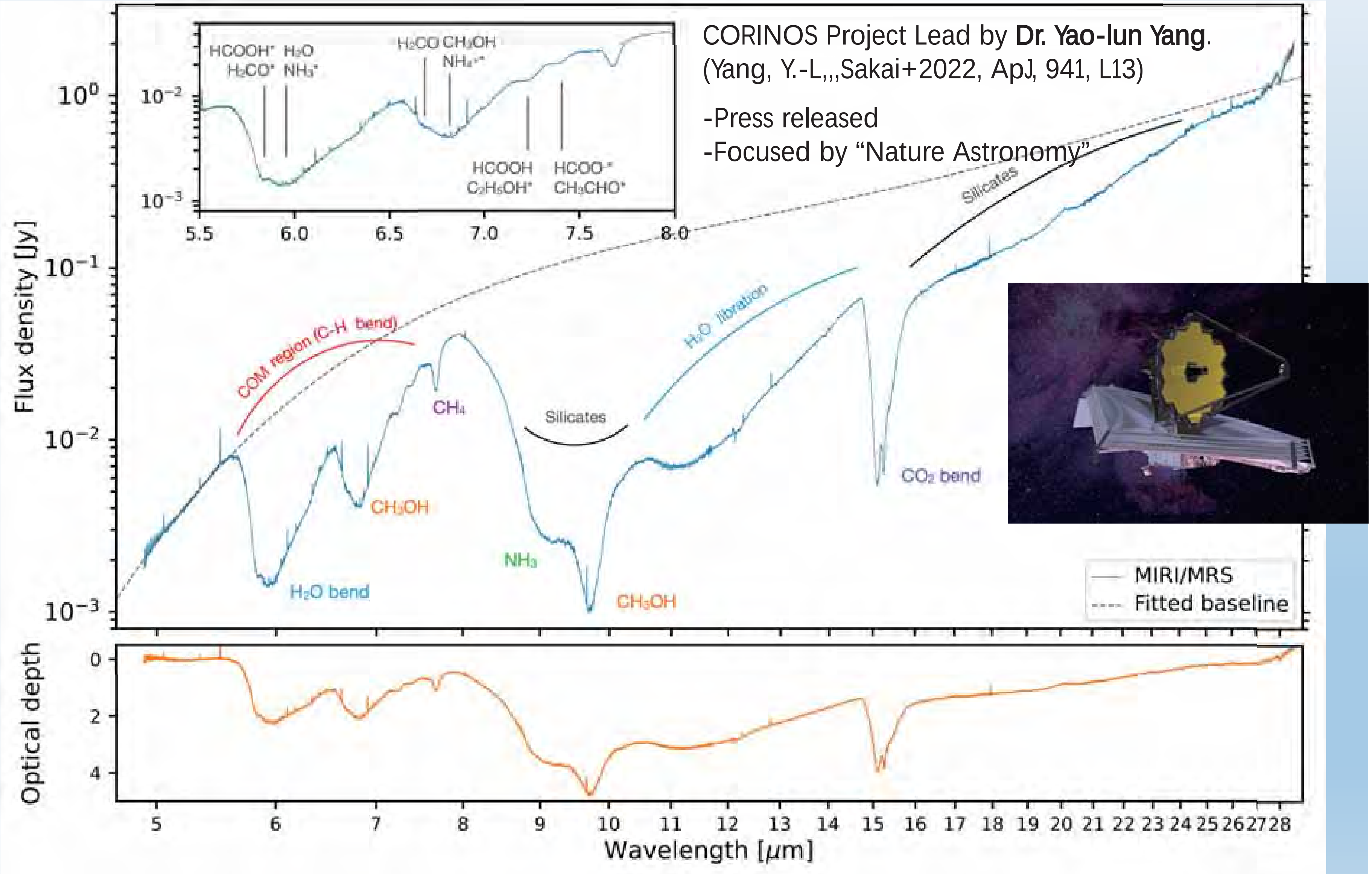
  Detailed chemical compositions in <a few 10s au scale

  ALMA Large Project FAUST (~70 members)

  Co-PIs: *Yamamoto, S., Ceccarelli, C., Chandler, C., Codella, C., and Sakai, N.*

  13 representative YSOs: e.g. Codella, C.,, Sakai+2021, *Frontiers in A.S.S.* 8, 782006

Chemistry in Icy Grain Mantles

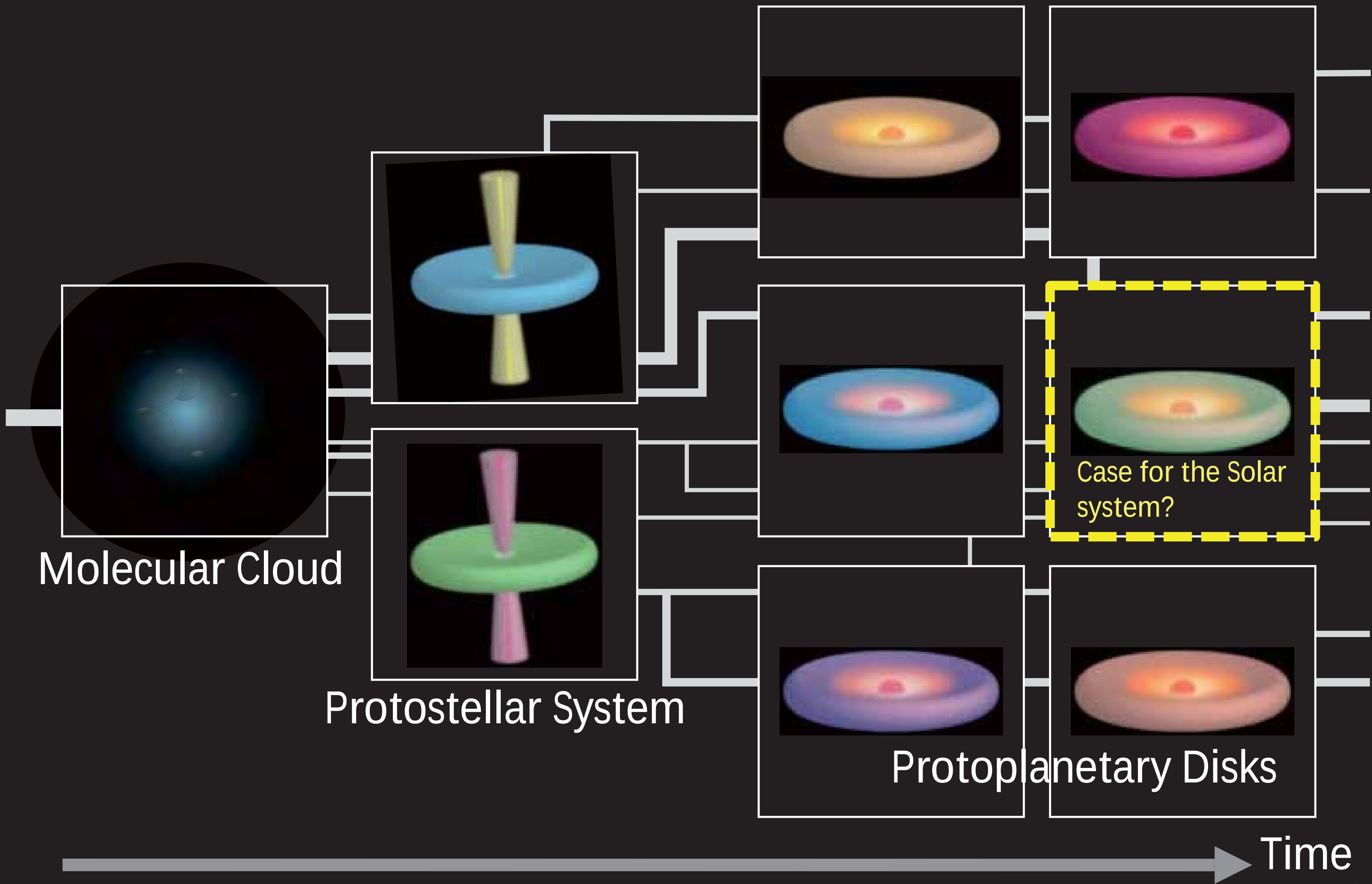


CORINOS Project Lead by **Dr. Yao-lun Yang**.
(Yang, Y.-L,,,Sakai+2022, ApJ, 941, L13)

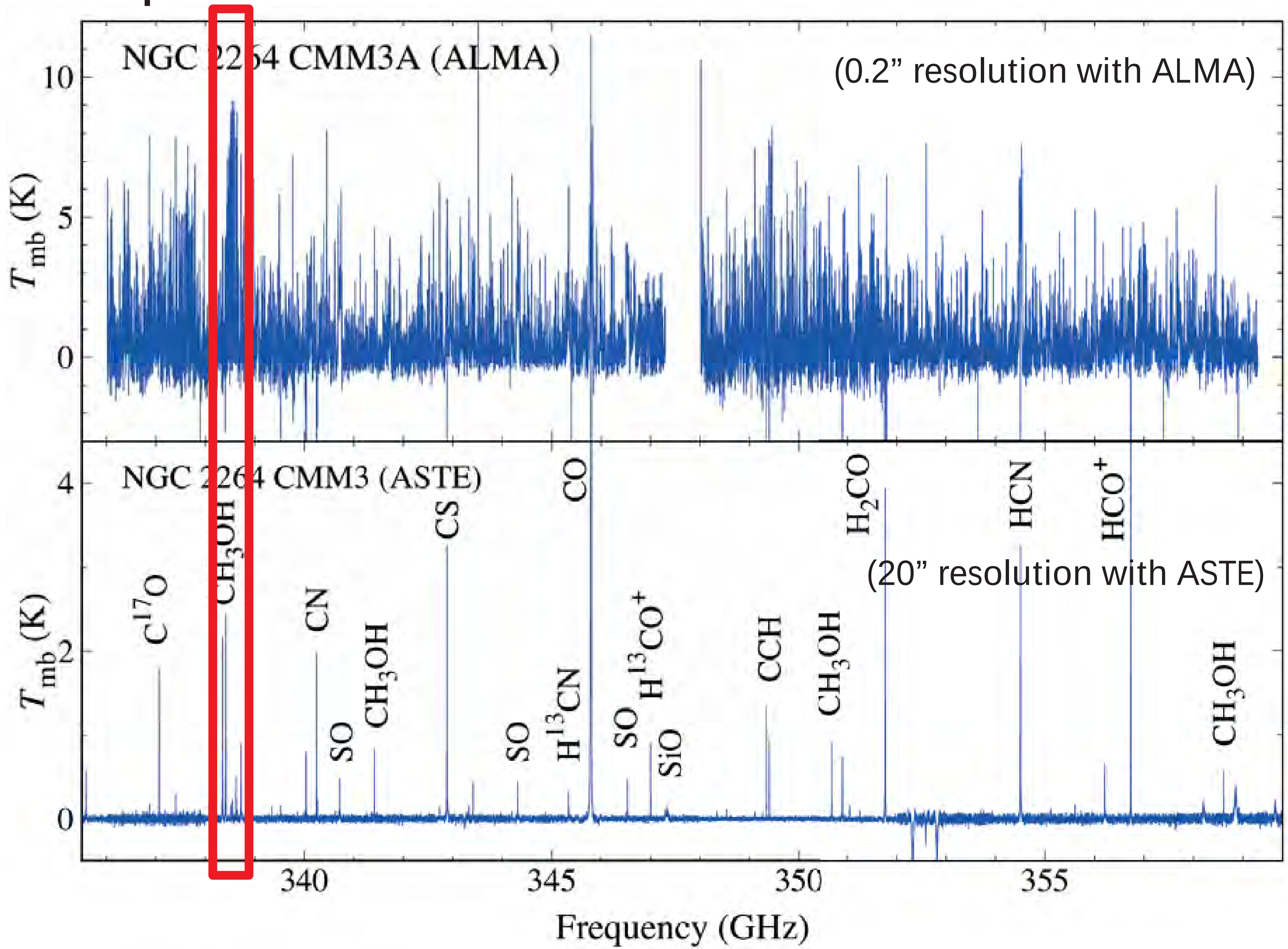
-Press released
-Focused by "Nature Astronomy"

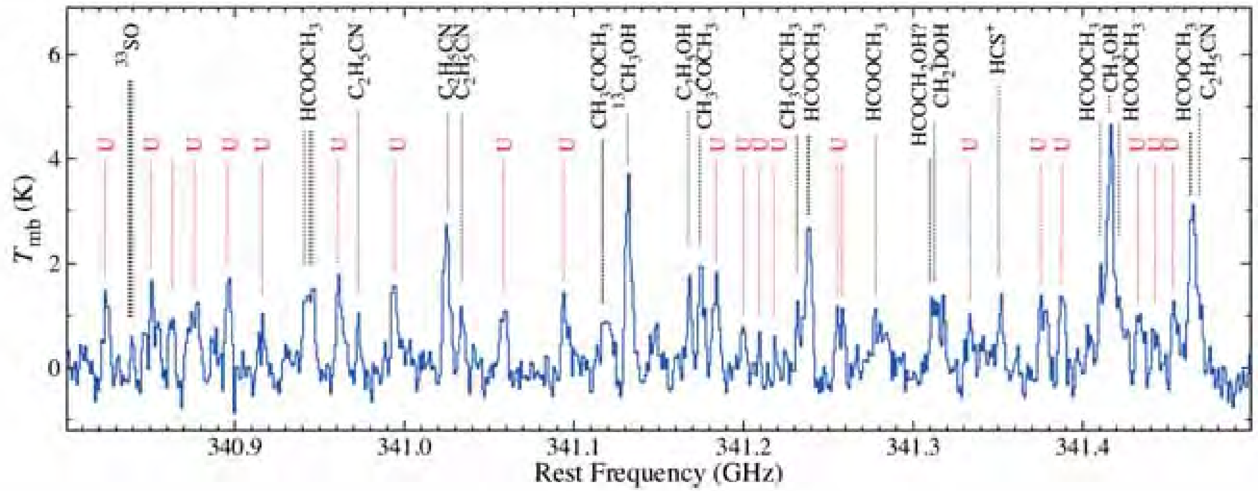
JWST MIRI MRS spectrum of a Class 0 protostar IRAS 15398-3359

Locate our Solar system in the diversity

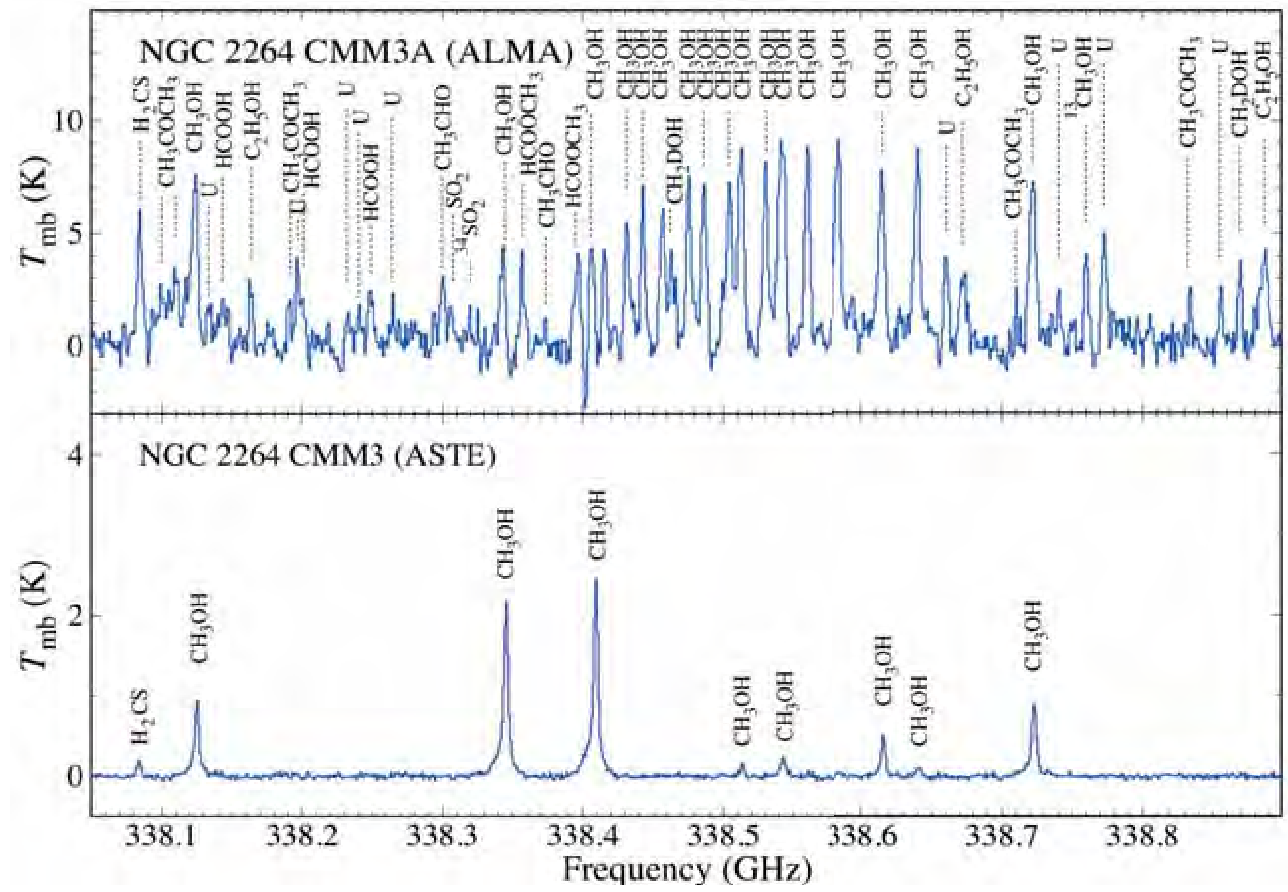


Spectrum taken toward NGC2264CMM3A





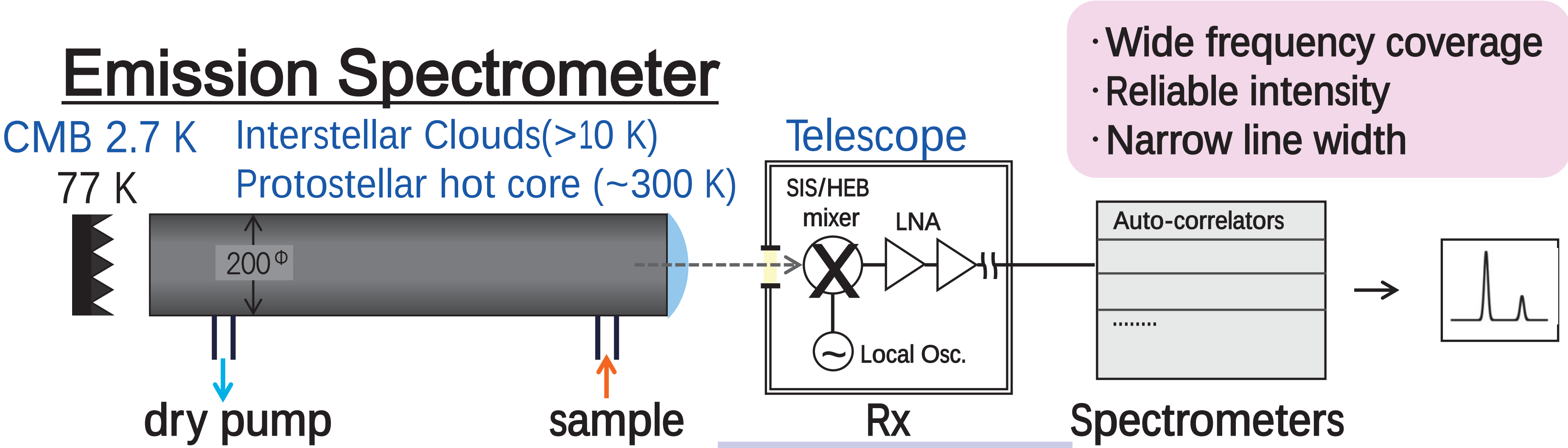
T_{mb} (K)
Rest Frequency (GHz)



NGC 2264 CMM3A (ALMA)
NGC 2264 CMM3 (ASTE)
T_{mb} (K)
Frequency (GHz)

Observing Gas Cell instead of the Sky

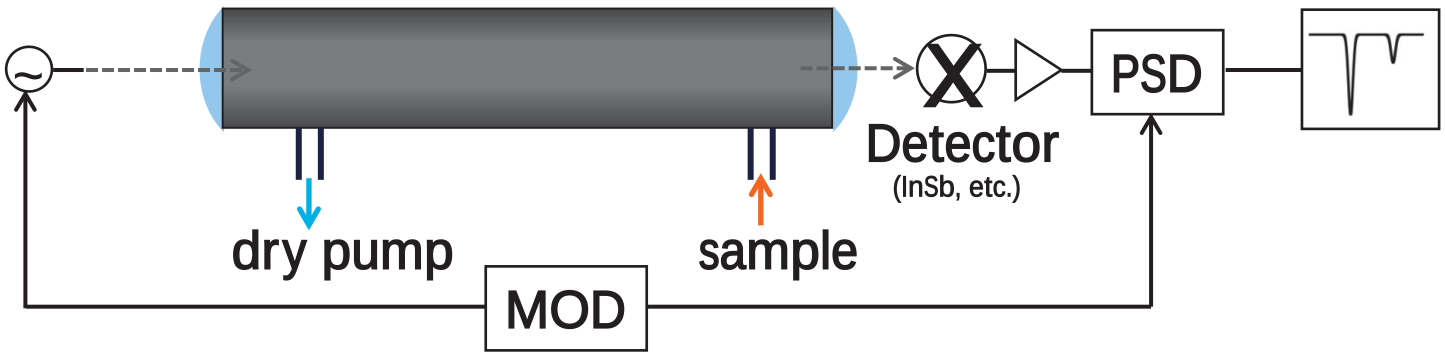
Emission Spectrometer



--UEC, UT, NAOJ--

Disadvantage: low sensitivity for 1 line detection

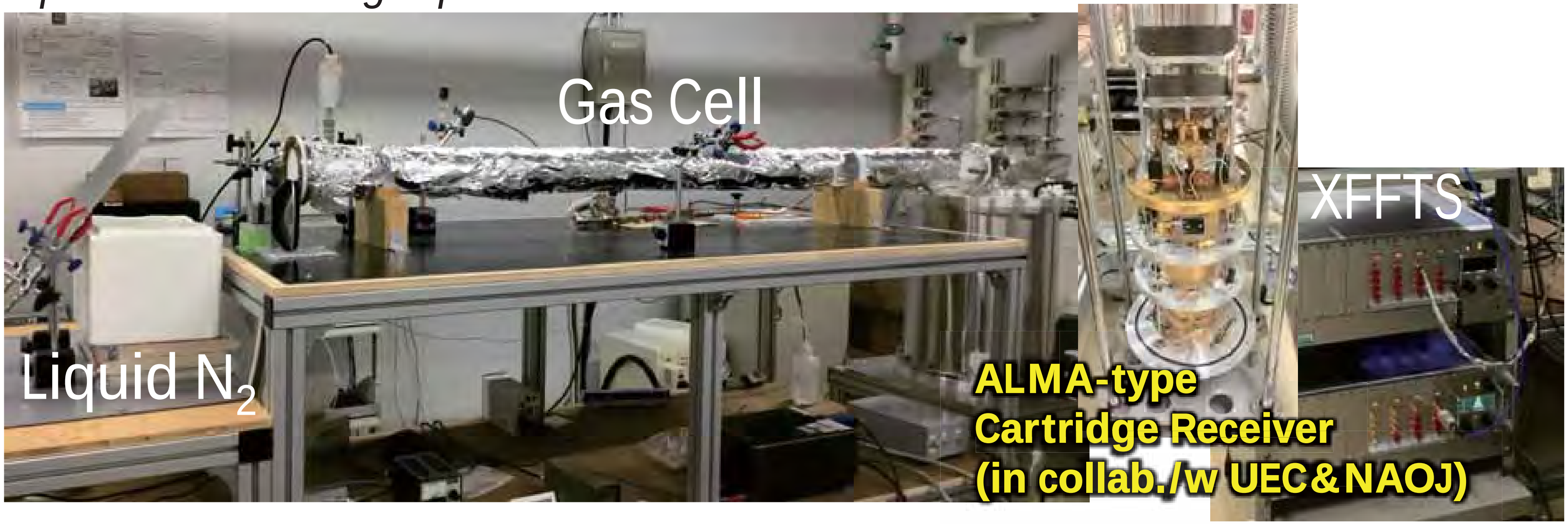
Conventional Absorption Spectrometer

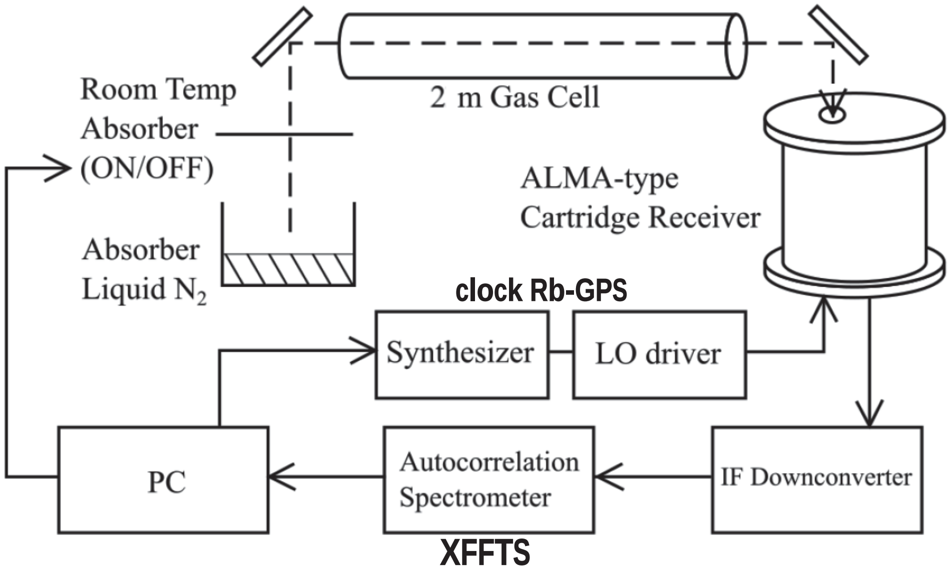


(Watanabe, Y.,,,Sakai,N+2021, PASJ, 73, 372)

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

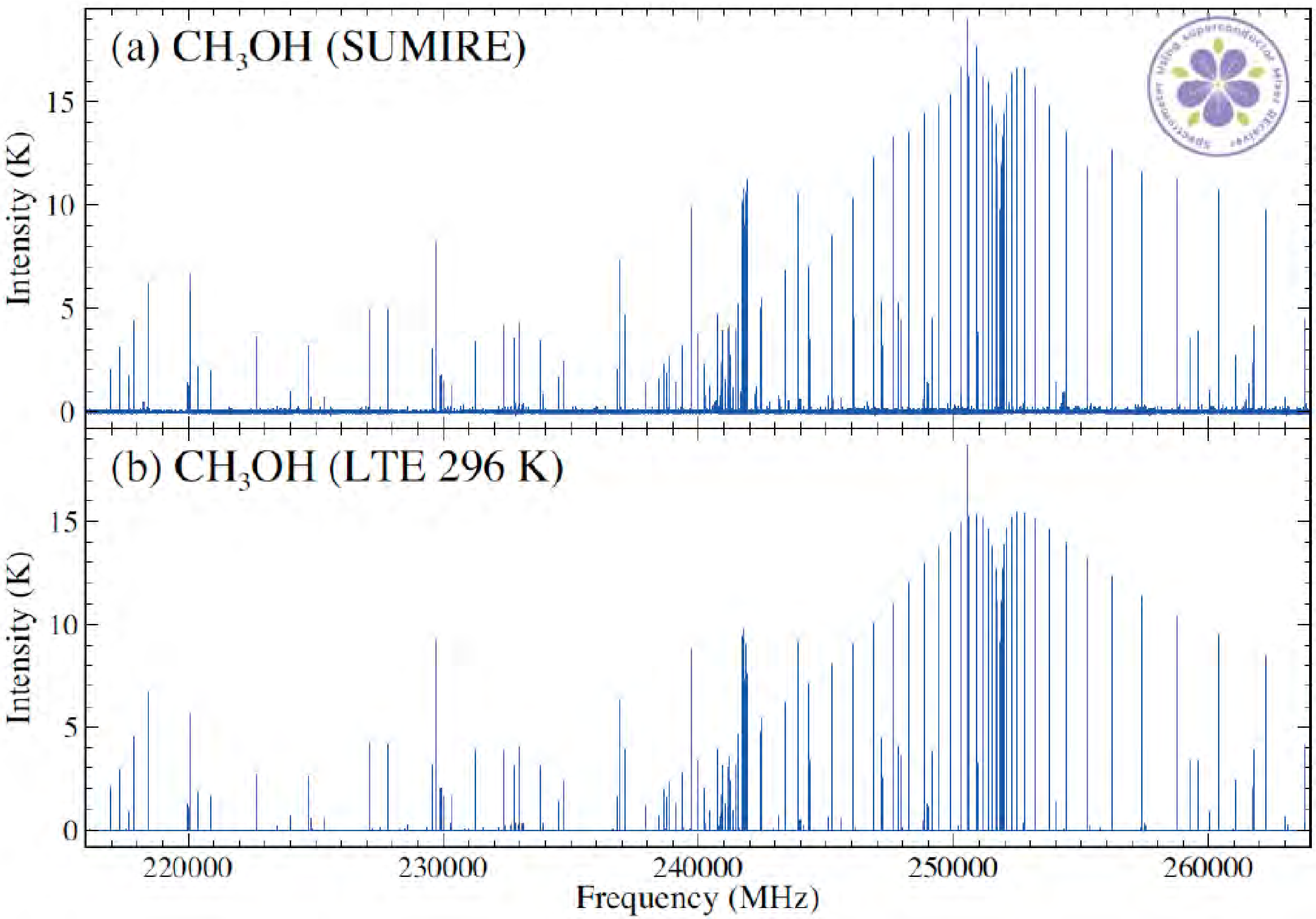
Int. accuracy: 5-10%

Determine

accurate frequency &

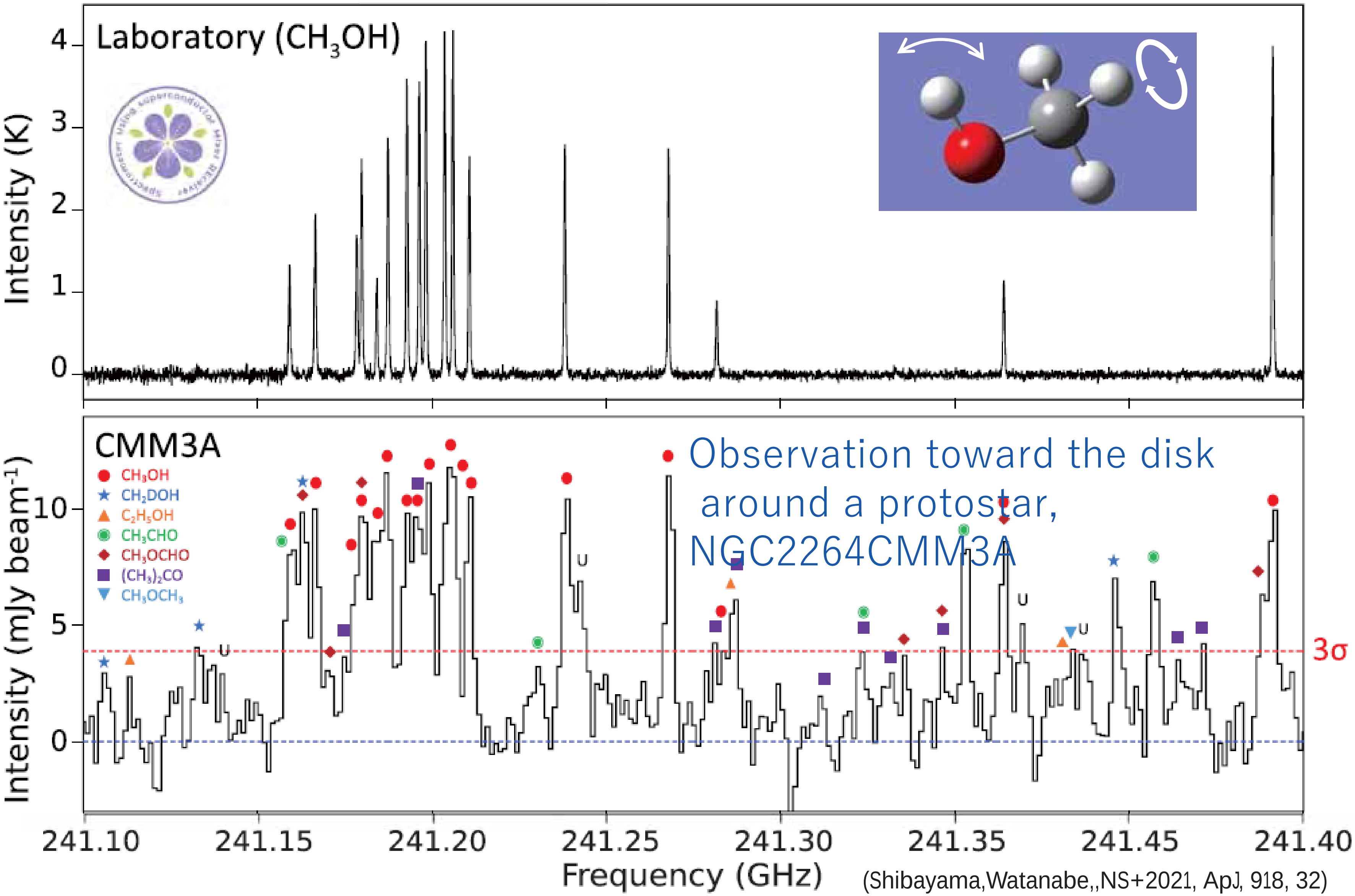
absolute intensity ($S\mu^2$)

CH_3OH Spectrum taken by SUMIRE



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

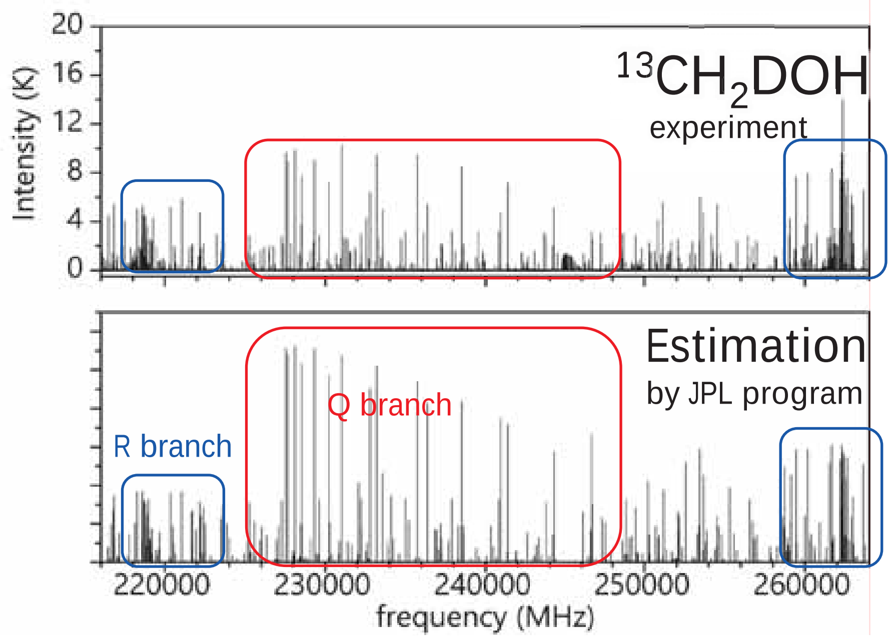
Origin of the "Weeds": Torsionally Excited Lines (v_t=1)

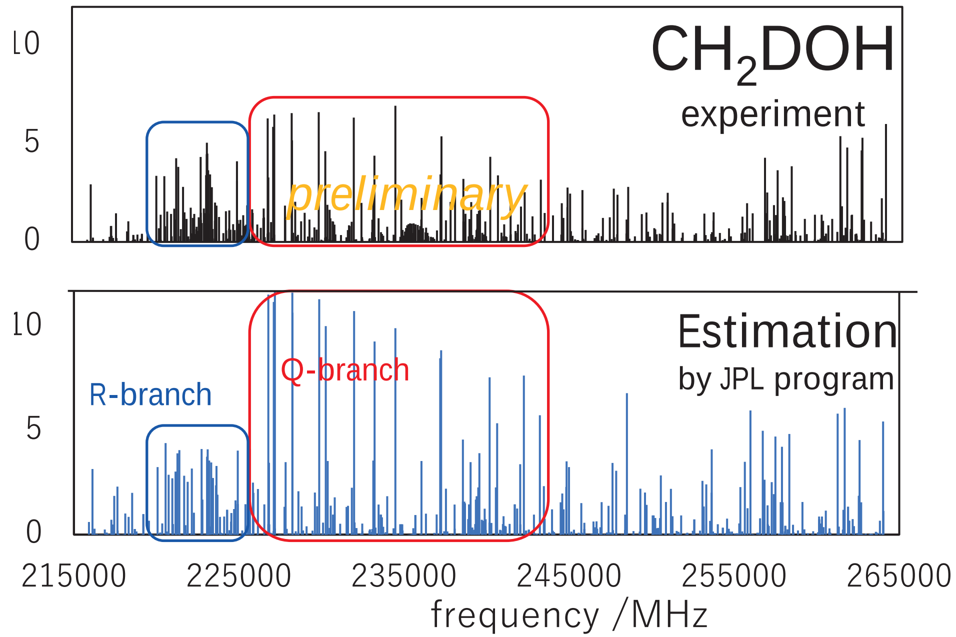


(Shibayama,Watanabe,,NS+2021, ApJ, 918, 32)

Intensity-Calibrated Spectroscopy

Works lead by Dr. Oyama, T.





(Ohno, Y., Oyama, T., ,NS+2022, ApJ, 932, 101) (Oyama, T., NS+2023, in press.)

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.

Formation of Interstellar Molecules

Gas Phase

$10^2 – 10^8$ cm^{-3}, 10 – 100 K

A + B → C + D ○
A + B → AB ×

- Binary reaction
- Exothermic
- No reaction barrier

ex. $H_3^+ + C \rightarrow CH^+ + H_2$

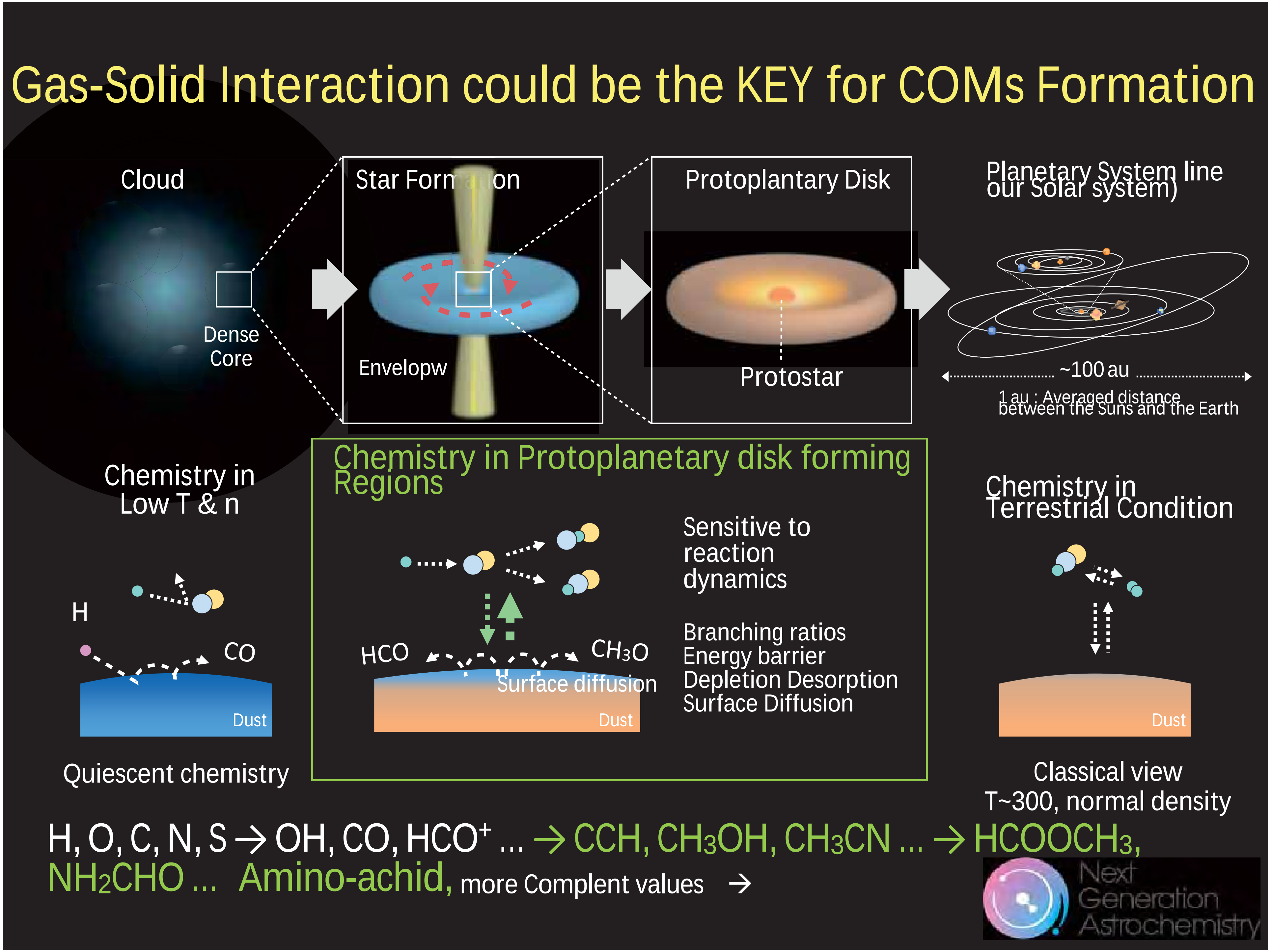
Grain Surface

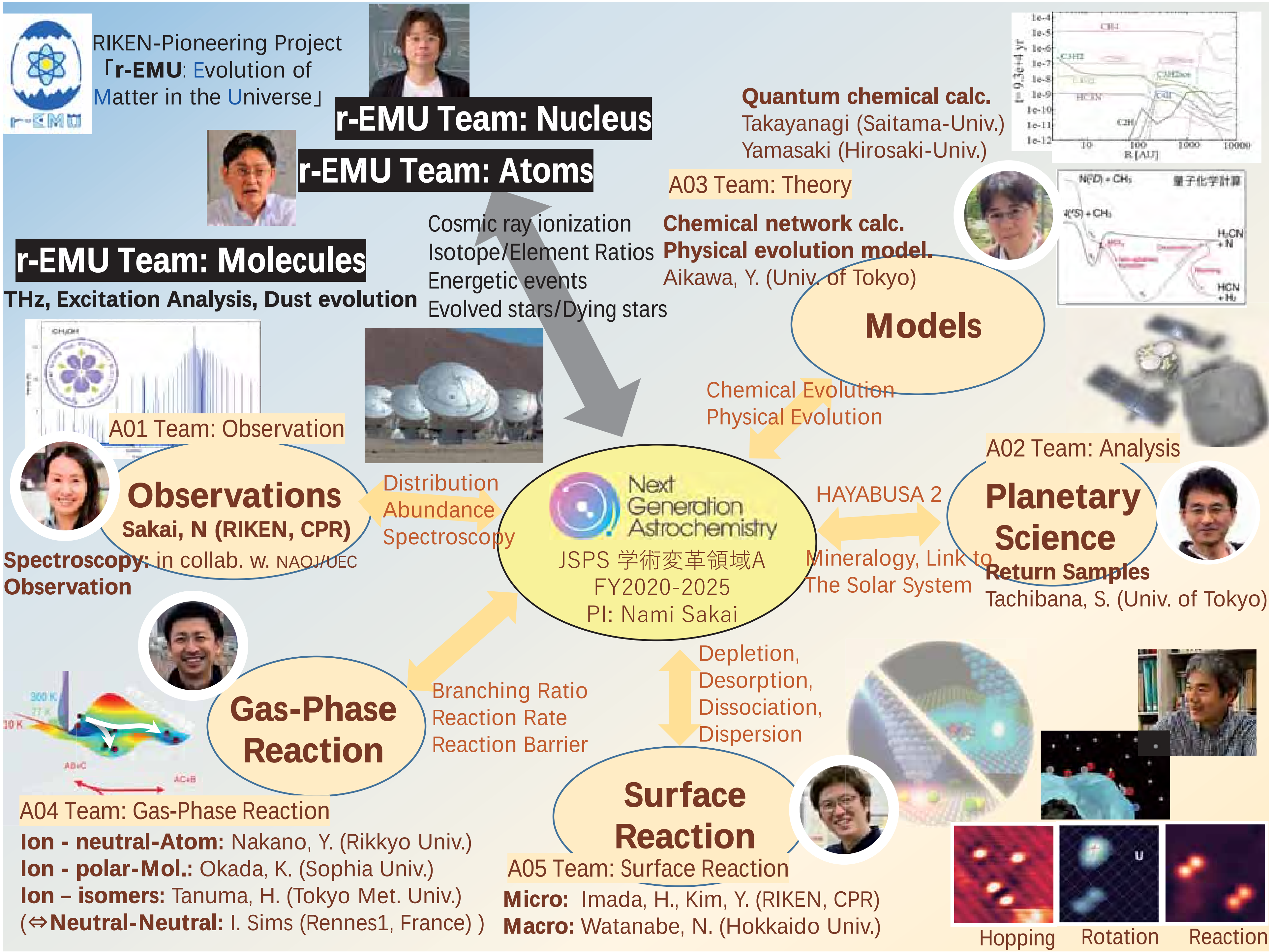
$M_{dust}/M_{gas} \sim 0.01$
Size ∼ 0.1 μm

- Hydrogenation
- Condensation

ex. O + H → OH
+ H → H_2O
CO+H → HCO
→→ CH_3OH

Photo: Taurus Molecular Cloud


Gas-Solid Interaction could be the KEY for COMs Formation
Cloud
Dense Core
Star Form ion
Envelopw
Protoplantary Disk
Protostar
Planetary System line our Solar system)
~100 au
1 au : Averaged distance between the Suns and the Earth
Chemistry in Low T & n
H
CO
Dust
Quiescent chemistry
Chemistry in Protoplanetary disk forming Regions
HCO
CH_3O
Surface diffusion
Dust
Sensitive to reaction dynamics
Branching ratios
Energy barrier
Depletion Desorption
Surface Diffusion
Chemistry in Terrestrial Condition
Dust
Classical view
T~300, normal density
H, O, C, N, S → OH, CO, HCO^+ ... → CCH, CH_3OH, CH_3CN ... → $HCOOCH_3$, NH_2CHO ... Amino-achid, more Complent values →
Next Generation Astrochemistry

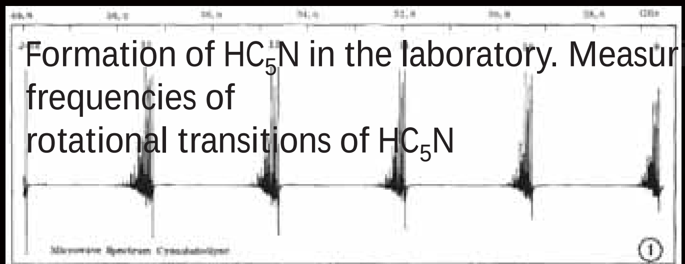

RIKEN-Pioneering Project
「r-EMU: Evolution of Matter in the Universe」
r-EMU Team: Nucleus
r-EMU Team: Atoms
r-EMU Team: Molecules
THz, Excitation Analysis, Dust evolution
Cosmic ray ionization
Isotope/Element Ratios
Energetic events
Evolved stars/Dying stars
Quantum chemical calc.
Takayanagi (Saitama-Univ.)
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
Depletion,
Desorption,
Dissociation,
Dispersion
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))
Surface Reaction
A05 Team: Surface Reaction
Micro: Imada, H., Kim, Y. (RIKEN, CPR)
Macro: Watanabe, N. (Hokkaido Univ.)
Hopping
Rotation
Reaction

ex) Innovation Originates from "Astrochemistry"

Carbon-chain molecules

HC_5N

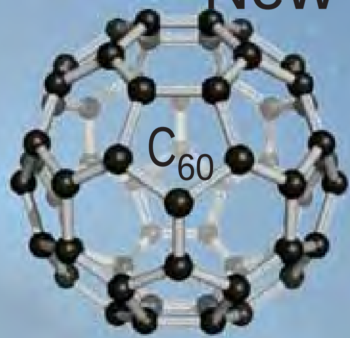
L. W. Avery, N. W. Broten, J. M. MacLeod,
T. Oka, and H. W. Kroto, ApJ, 205 (1976), L173



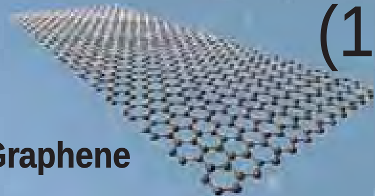
Formation of HC_5N in the laboratory. Measuring rest frequencies of rotational transitions of HC_5N

A.J. Alexander, H.W. Kroto, D.R.M. Walton
J. Mol. Spectrosc., 62 (1976), pp. 175–180

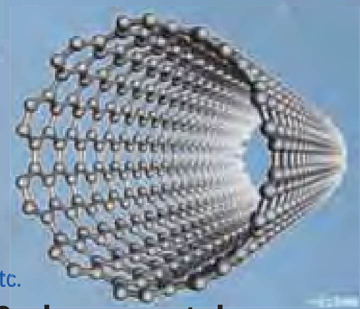
New field of nanoscience (1990~)



Fullerene



Graphene

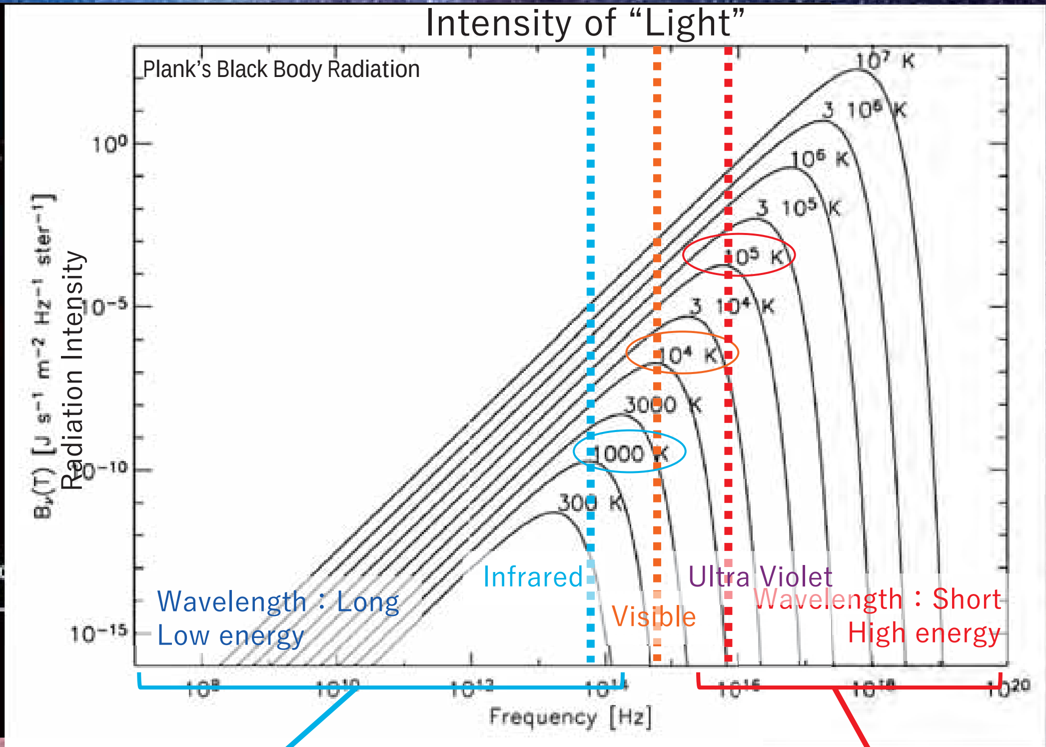


Carbon nanotube

Superconductivity, Photo Absorbent, Catalyst, Low Thermal Conductivity, Free radical Scavenger, Cage Structure, Electron Accepter, etc.

(→Fuel Cell, Conductive Transparent Thin Film, Electronic Conductive Papers/Fibers, Biosensor, Drug Delivery System....)

Solar Radiation vs Excitation Energy of Molecules
～ Coincidence? ～



Solar Radiation have a peak at ~500 nm
→ 2.5 eV

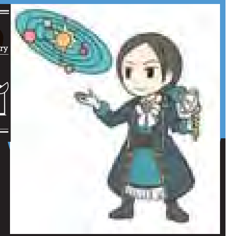
Similar to the energy to excite "valence electrons" in molecules

Radiation energy can be converted to chemical energy
→Chemical reactions

Low energy photon
Can not excite "valence-electrons" in molecules

High energy photon
Mainly destroys molecules
ex）C-H bond: 4-5 eV
cf）Skin damage by UV

Star and Planet Formation Laboratory



Next Generation Astrochemistry

Themes & Members

Chief Scientist: Nami Sakai

Theme (A) Chemical Evolution from Clouds to Planets
Yao-lun Yang, Ziwei Zhang, Shaoshan Zeng,
Yuki Okoda, Yui Kawashima, (Shota Notsu@UT)

Theme (B) Star and Planet Formation
Naida Murillo, Ross Burns, Ryota Tominaga,
(Riouhei Nakatani@JPL), (Yichen Zhang@UVA), (Satoshi Ohashi @NAOJ)

Theme (C) Tools: Spectroscopy & Dust Experiments
Takahiro Oyama, Akemi Tamanai, (Satoshi Ohashi @NAOJ),
(Yoshimasa Watanabe @SIT & Students), (Takeshi Sakai @UEC & Students)

As of Apr. 2023 PI, Sub-leader (Staff Scientist), PD, SPDR, (Visiting-Staff)

Supported by

開拓研究本部 Cluster for Pioneering Research
科研費 KAKENHI
JSPS

Main Collaborators

NAOJ National Astronomical Observatory of Japan
東京大学 大学院 理学系研究科・理学部
CNRS
UEC TOKYO