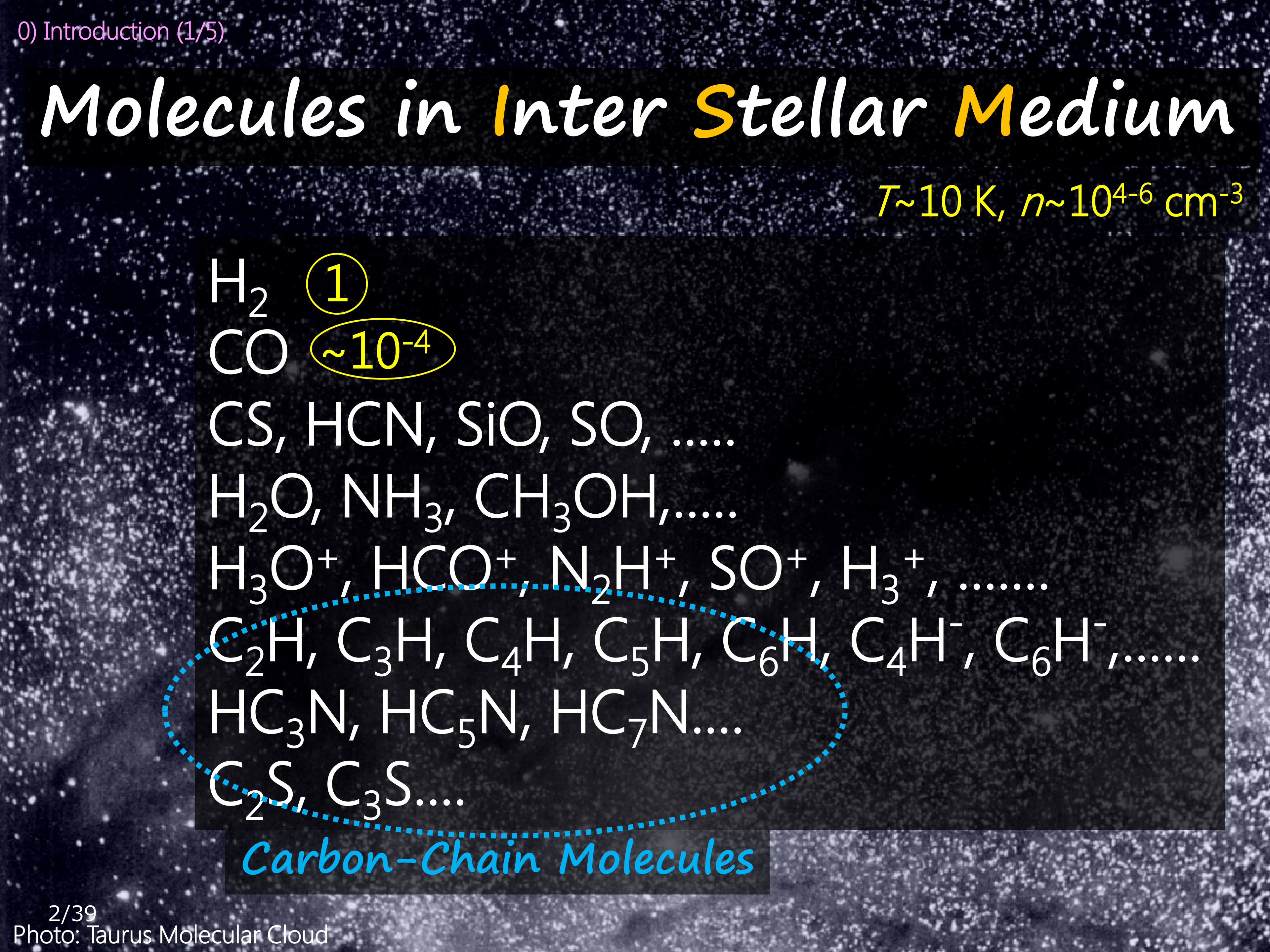
RIKEN 東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO cnrs Max-Planck-Institut für Radioastronomie 科研費 KAKENHI

Astrochemical Approach to Star and Planet Formation

Nami Sakai
(RIKEN from April 2015)

Photo: Cygnus

Molecules in Inter Stellar Medium



$T \sim 10$ K, $n \sim 10^{4\text{-}6}$ cm^{-3}

H_2 1

CO $\sim 10^{-4}$

CS, HCN, SiO, SO, ...

H_2O, NH_3, CH_3OH,.....

H_3O^+, HCO^+, N_2H^+, SO^+, H_3^+, ...

C_2H, C_3H, C_4H, C_5H, C_6H, C_4H^-, C_6H^-,......

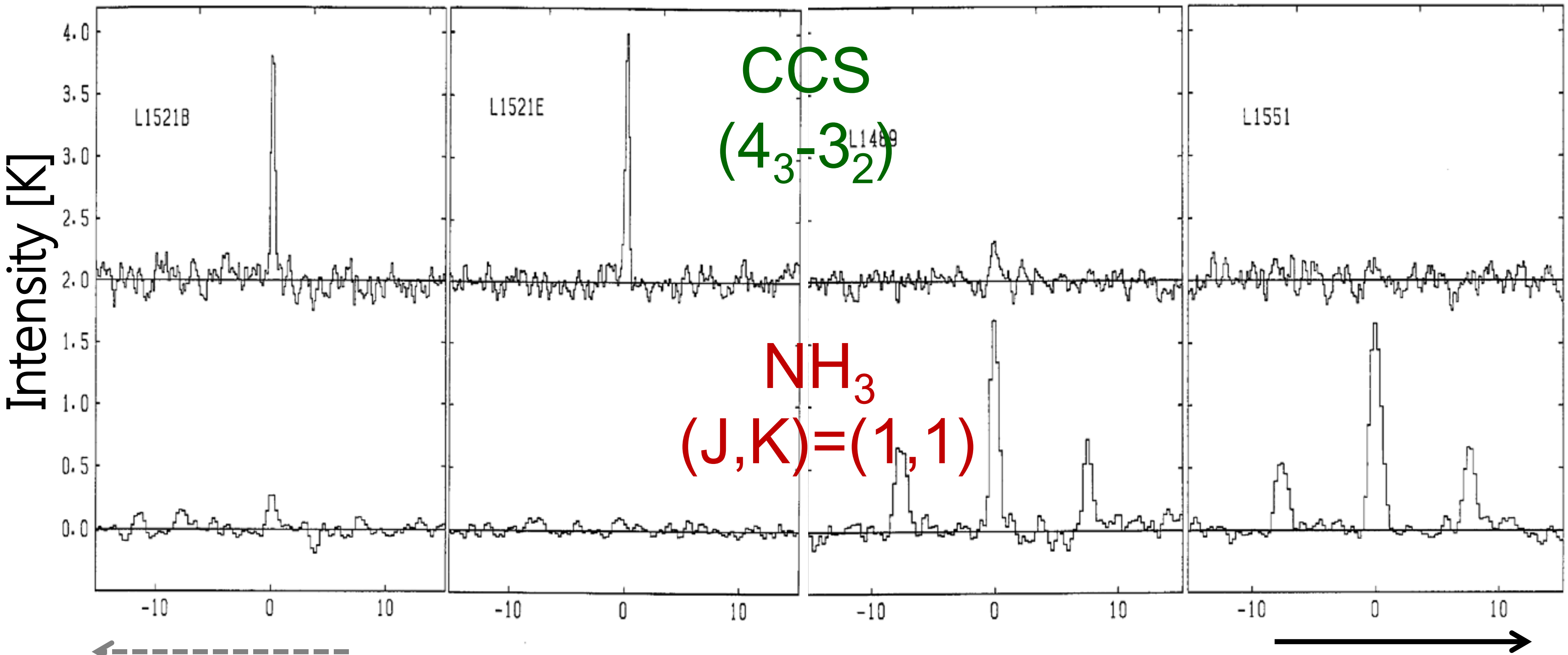
HC_3N, HC_5N, HC_7N....

C_2S, C_3S....

Carbon-Chain Molecules

Photo: Taurus Molecular Cloud

Chemical Evolution toward Star Formation



(Suzuki et al. 1992, ApJ, 392, 551)

Non-equilibrium Chemistry

Time Scale for Chemical Equilibrium

Formation : τ_f ~10^6 yr

Destruction : τ_d ~10^7 yr (Dense cloud: Ionic destruction →slow)
(~10^2 yr Diffuse cloud: Photodissociation→ fast)

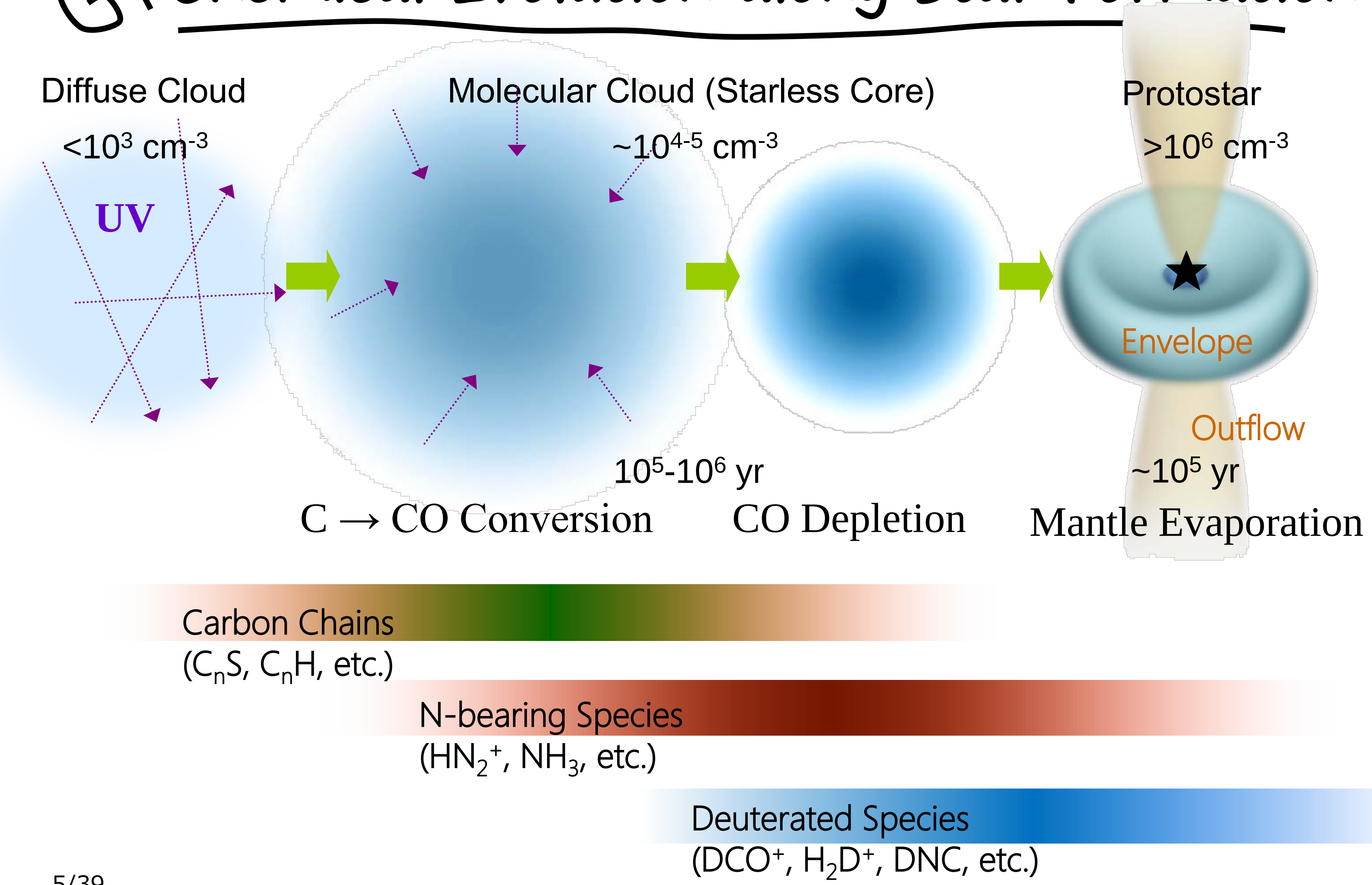
$$\mathrm{A} \underset{\tau_d}{\overset{\tau_f}{\rightleftarrows}} \mathrm{A'} \qquad \frac{1}{\tau} = \frac{1}{\tau_f} + \frac{1}{\tau_d} \Rightarrow \tau \sim 10^6 \text{ yr}$$

$$\tau \gtrsim \tau_{\mathrm{dyn}}$$

Free fall time of actual cloud cores

$$t_{\text{free fall}} = \frac{4 \times 10^5}{\sqrt{n/10^4 \text{ cm}^{-3}}} \text{ yr}$$

Chemical Evolution along Star Formation



Diffuse Cloud

$<10^3$ cm^{-3}

UV

Molecular Cloud (Starless Core)

$\sim10^{4\text{-}5}$ cm^{-3}

10^5-10^6 yr

Protostar

$>10^6$ cm^{-3}

Envelope

Outflow

$\sim10^5$ yr

C → CO Conversion

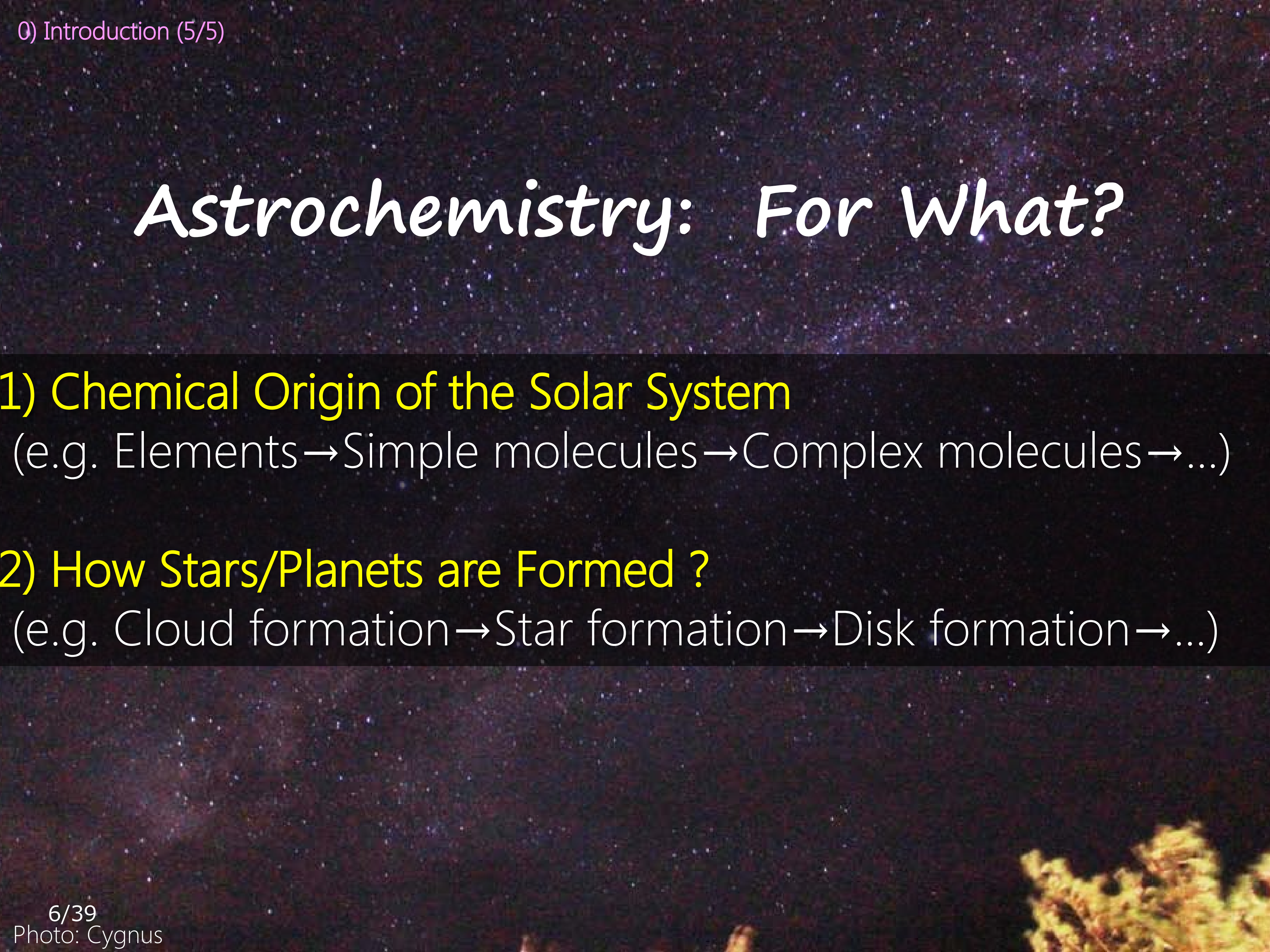
CO Depletion

Mantle Evaporation

Carbon Chains
(C_nS, C_nH, etc.)

N-bearing Species
(HN_2^+, NH_3, etc.)

Deuterated Species
(DCO^+, H_2D^+, DNC, etc.)



Astrochemistry: For What?

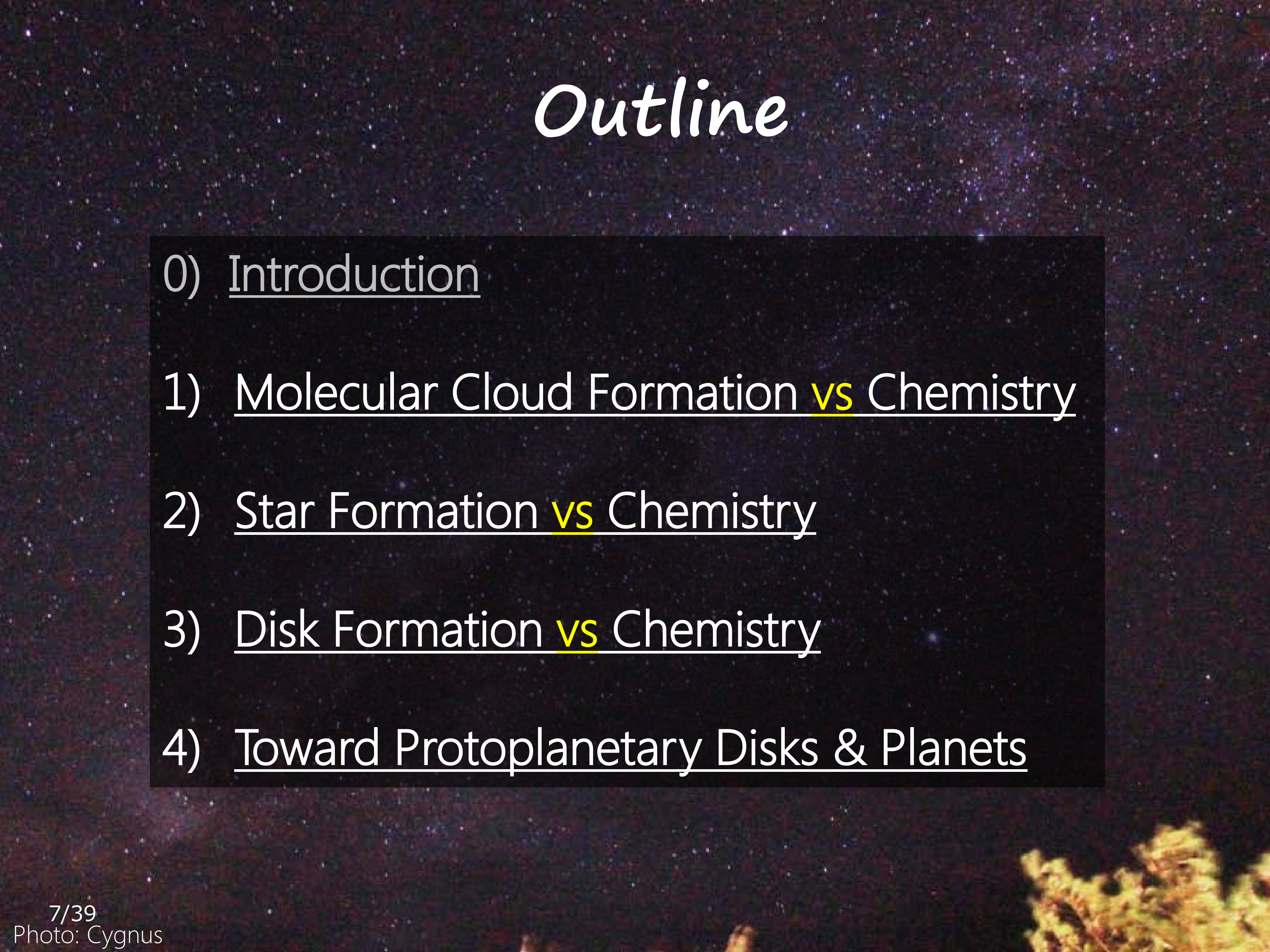
1) Chemical Origin of the Solar System

(e.g. Elements→Simple molecules→Complex molecules→…)

2) How Stars/Planets are Formed ?

(e.g. Cloud formation→Star formation→Disk formation→…)

Photo: Cygnus



Outline

0) Introduction

1) Molecular Cloud Formation vs Chemistry

2) Star Formation vs Chemistry

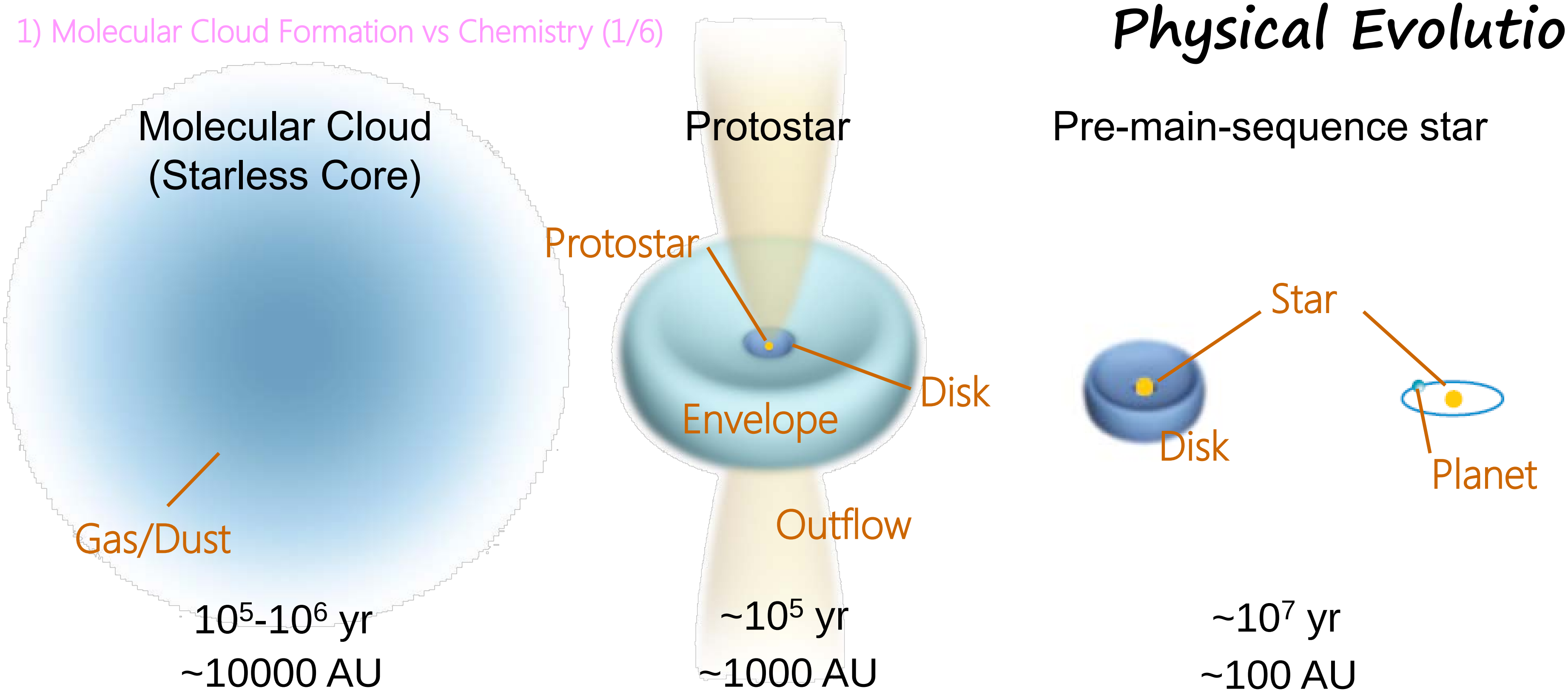
3) Disk Formation vs Chemistry

4) Toward Protoplanetary Disks & Planets

Photo: Cygnus

1) Molecular Cloud Formation vs Chemistry (1/6)

Physical Evolution



Molecular Cloud (Starless Core)	Protostar	Pre-main-sequence star
10^5-10^6 yr	~10^5 yr	~10^7 yr
~10000 AU	~1000 AU	~100 AU

Chemical Evolution

C → CO Conversion

CO Depletion

Mantle Evaporation

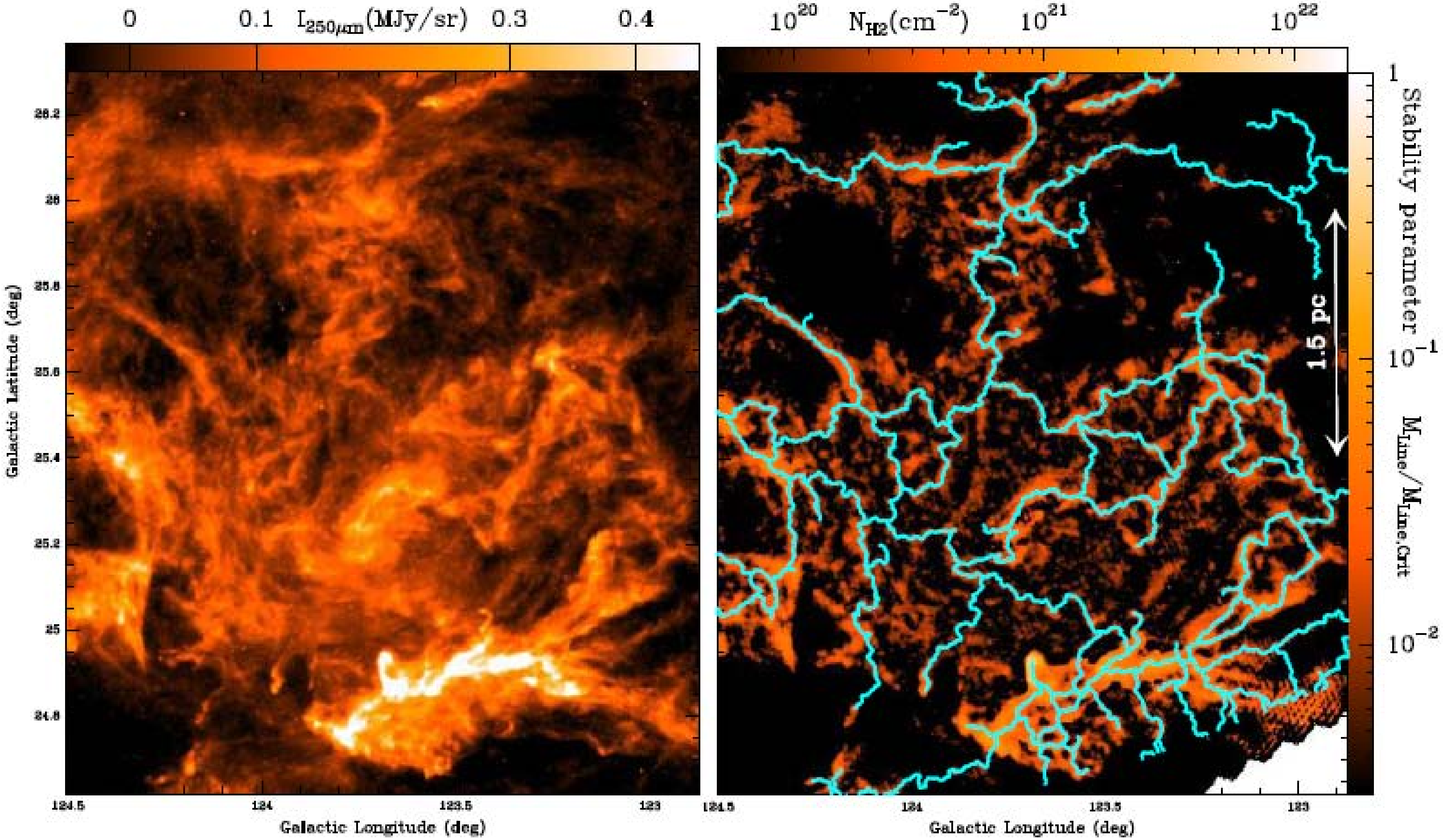
Carbon Chains

HN_2^+, NH_3

Deuterated Species

DCO^+, H_2D^+

Molecular Cloud Formation



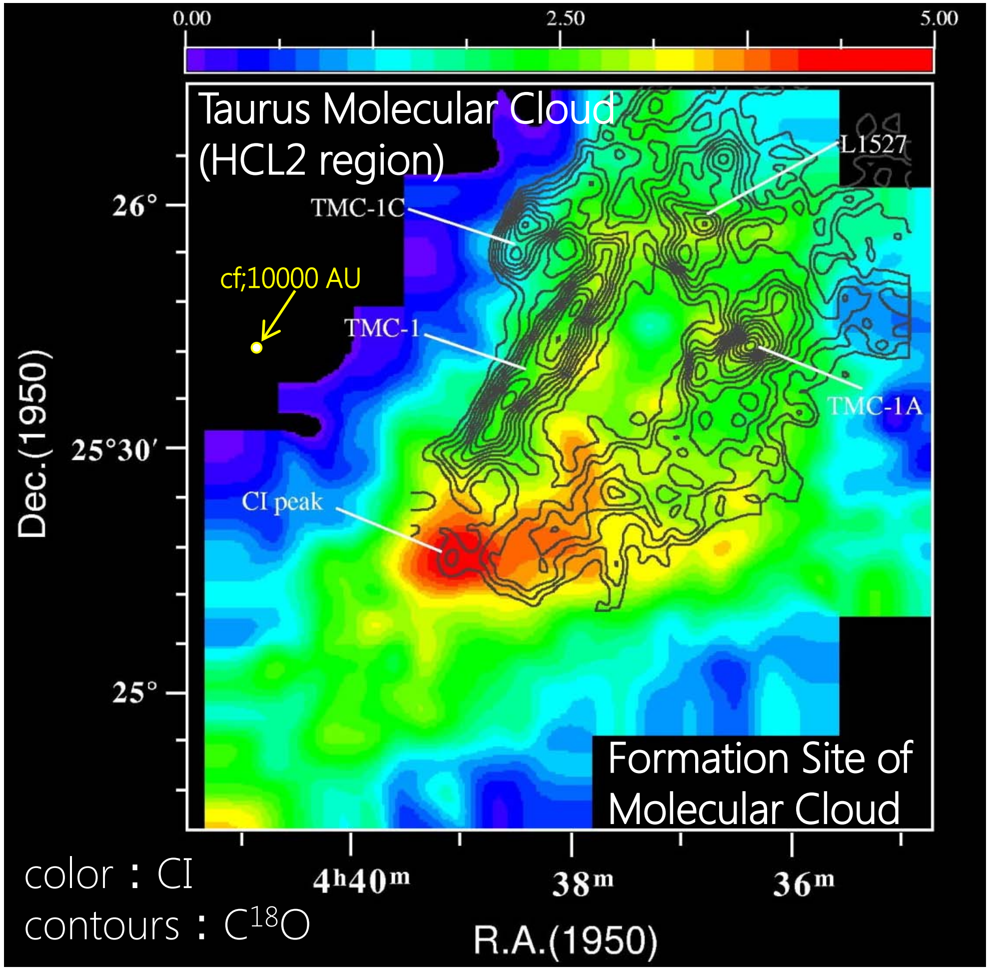
250 um continuum map

Column density map

(Miville-Deschenes et al. 2010; Ward-Thompson et al. 2010; Andre et al. 2010)

Chemical Diagnostics of Cloud Formation

C&CO map



Taurus Molecular Cloud (HCL2 region)

cf;10000 AU

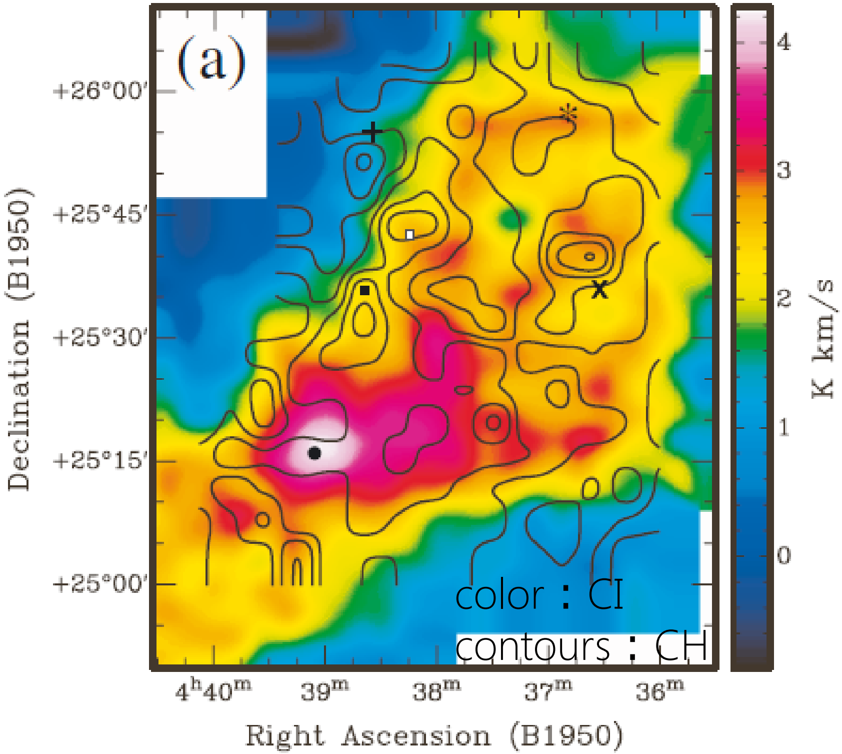
Formation Site of Molecular Cloud

color : CI
contours : $C^{18}O$

(Maezawa et al. 1999, ApJ., 524, L129)

$$C \xrightarrow{H_3^+,\ H_2} CH \xrightarrow{O} CO$$

C&CH map



color : CI
contours : CH

(Sakai et al. 2012, ApJ., 546, A103)

OH as a Tracer of Cloud Formation

Atomic Cloud ·····> Molecular Cloud

H, C, O

n~10-10^2 cm^{-3}

T~50-100 K

CO

n~10^3-10^6 cm^{-3}

T~10 K

CH/OH

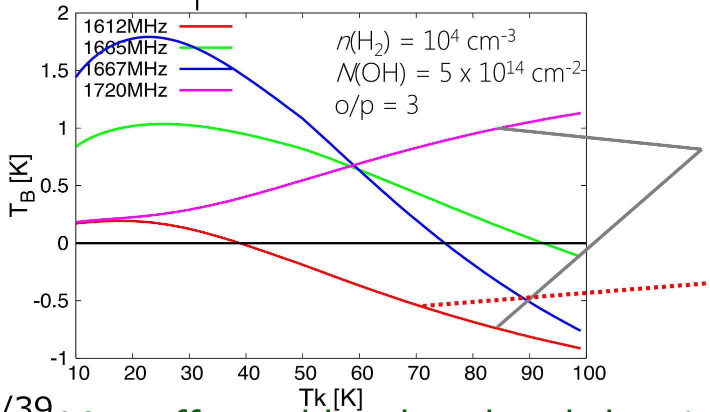
Hyperfine anomaly of the OH 18 cm line

In the LTE condition, (Critical density ~10 cm^{-3})

$T_{1612} : T_{1665} : T_{1667} : T_{1720} = 1 : 5 : 9 : 1$

⇩

Statistical equilibrium calculation with LVG

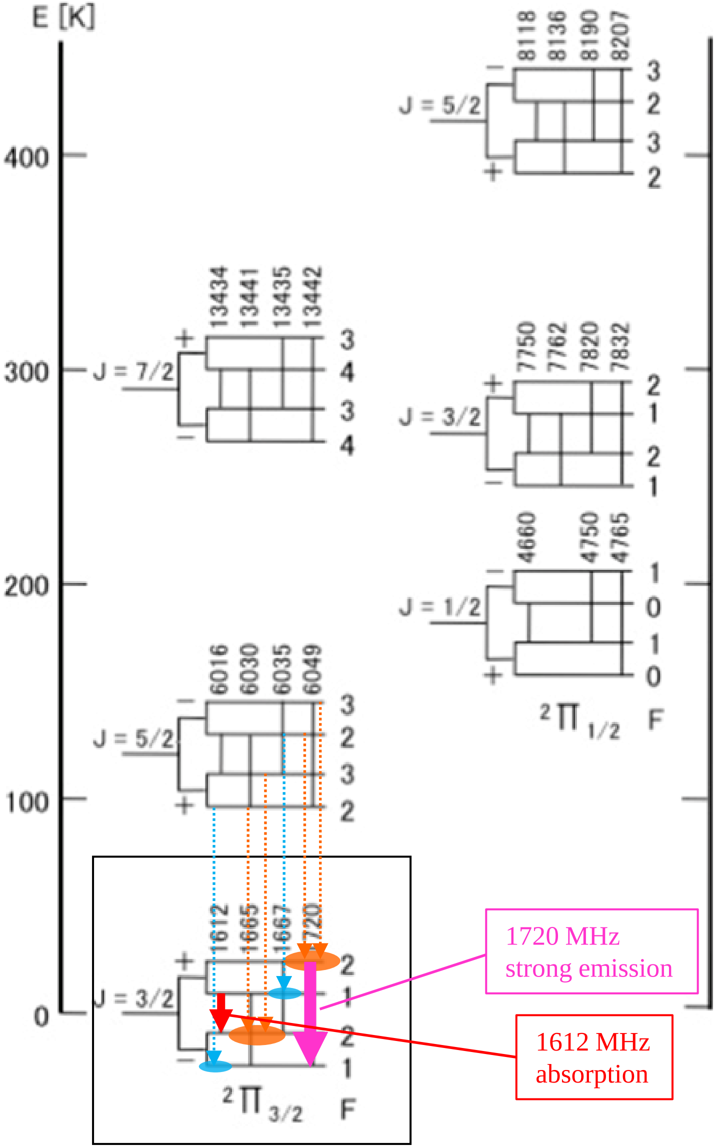


Conjugate behavior

T_k>40 K

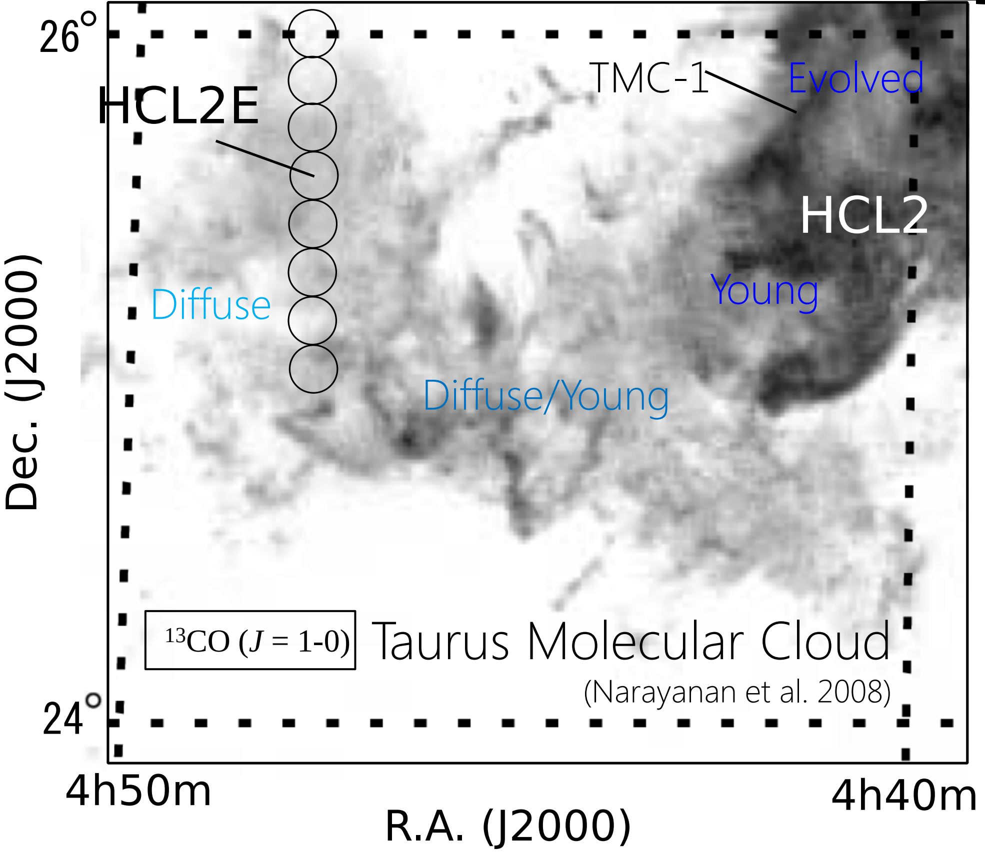
Absorption !

Not affected by the cloud density @10^2-10^7 cm^{-3}



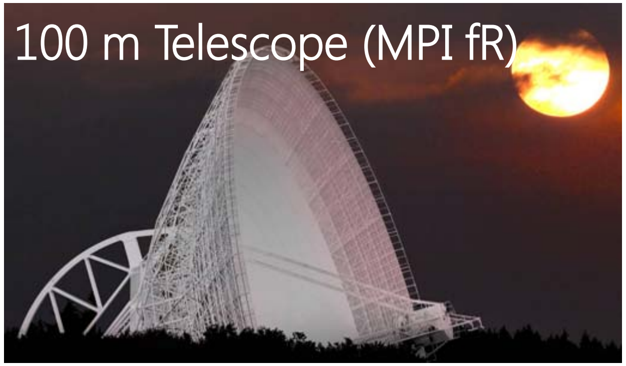
The rotational energy structure of OH

Temperature & Column-Density of HCL2E



Taurus Molecular Cloud

(Narayanan et al. 2008)



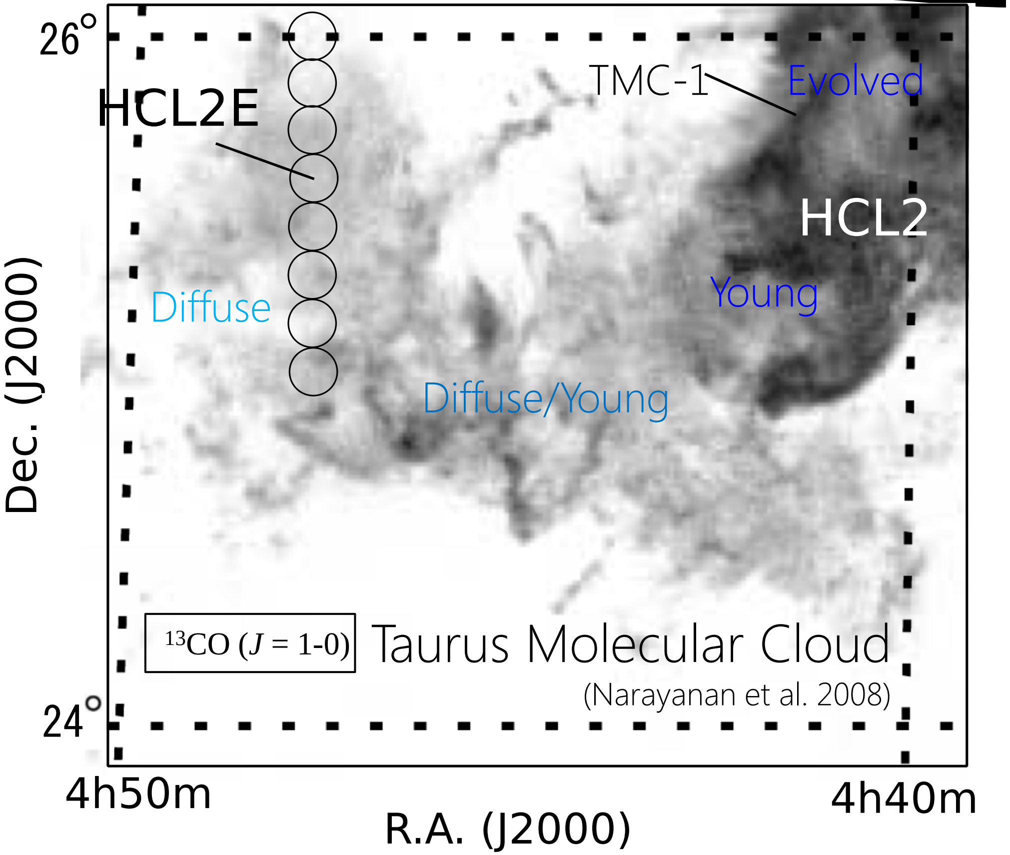
100 m Telescope (MPI fR)

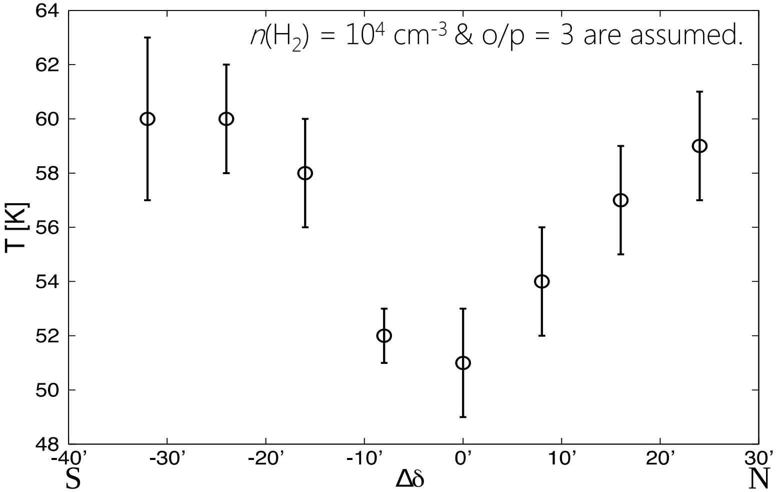
No radio continuum source

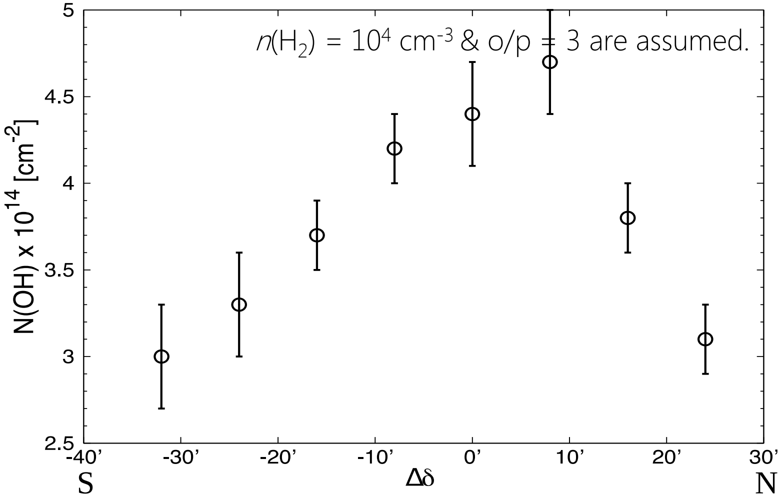
→ Absorption against CMB.

(Ebisawa, Sakai, et al. 2015, ApJ, submitted)

Temperature & Column-Density of HCL2E







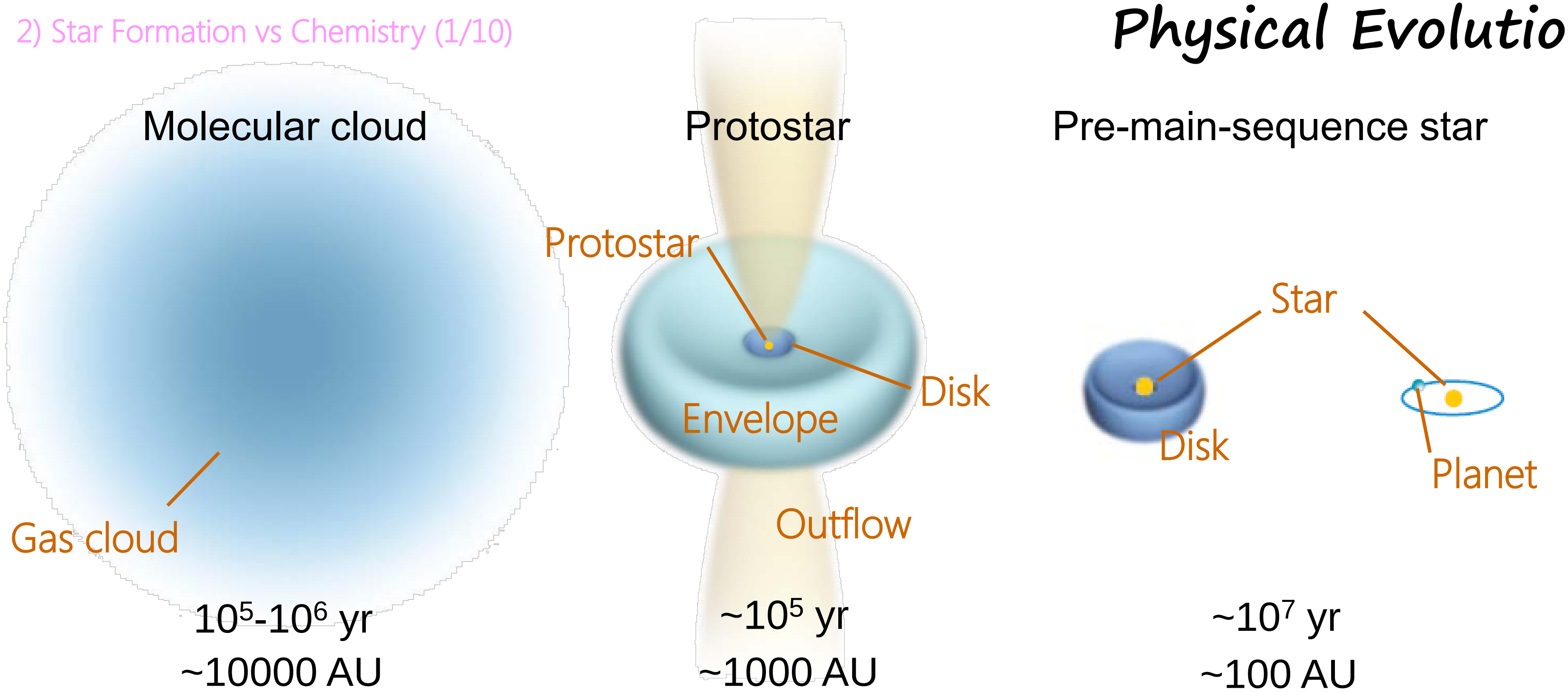
The OH lines can be used for the filament & Cloud core formation !

No radio continuum source

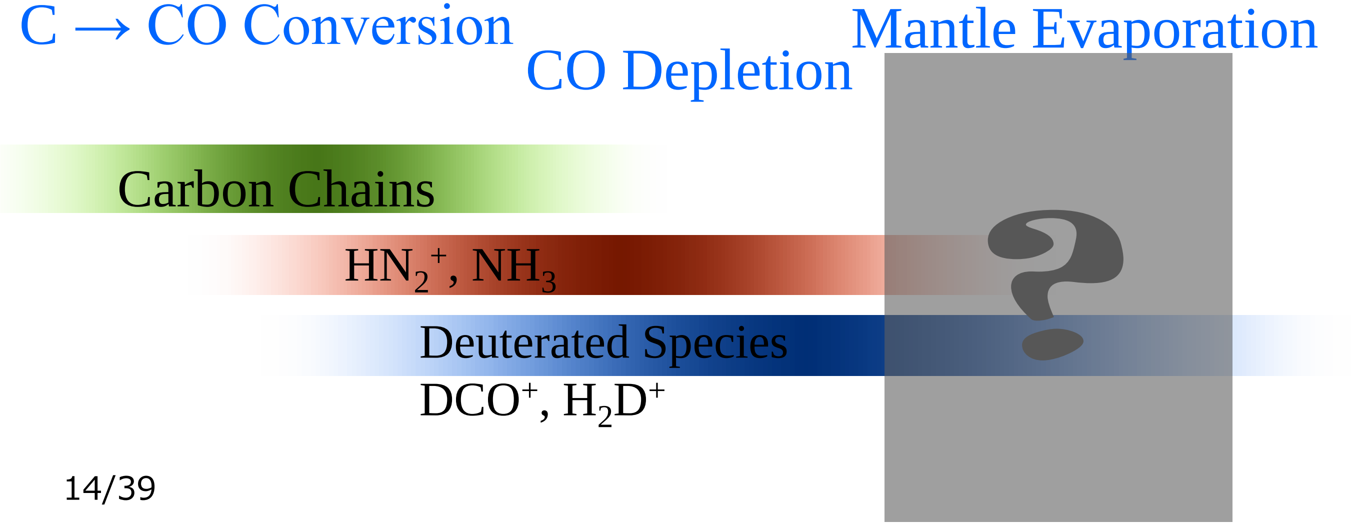
→ Absorption against CMB.

(Ebisawa, Sakai, et al. 2015, ApJ, submitted)

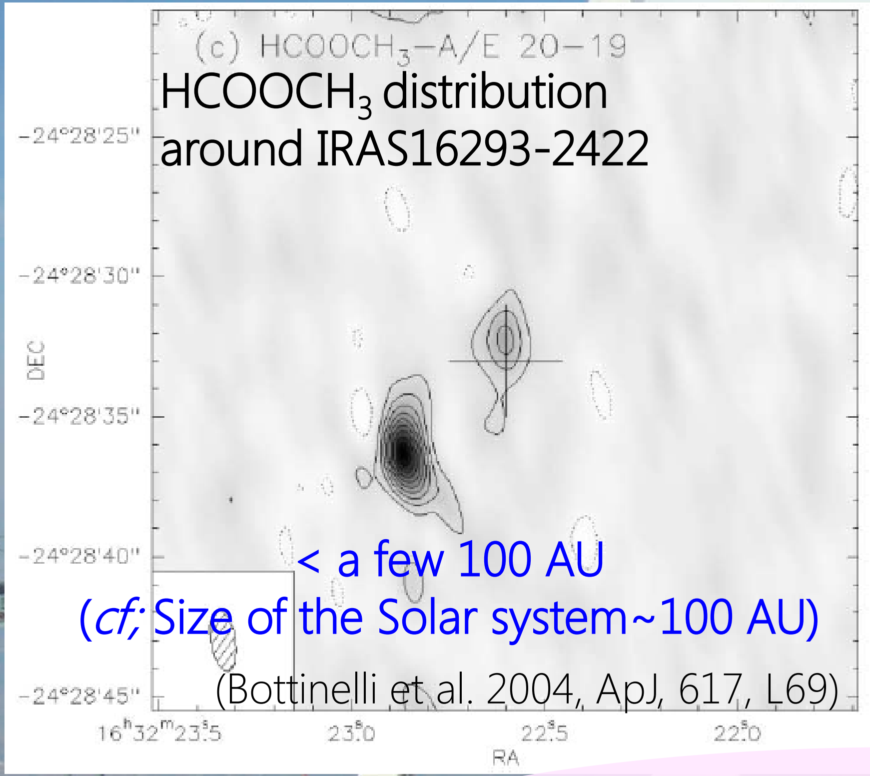
Physical Evolution



Chemical Evolution



Detections of "Complex" Organic Molecules (COMs)



$HCOOCH_3$ distribution around IRAS16293-2422

< a few 100 AU

(*cf;* Size of the Solar system~100 AU)

(Bottinelli et al. 2004, ApJ, 617, L69)

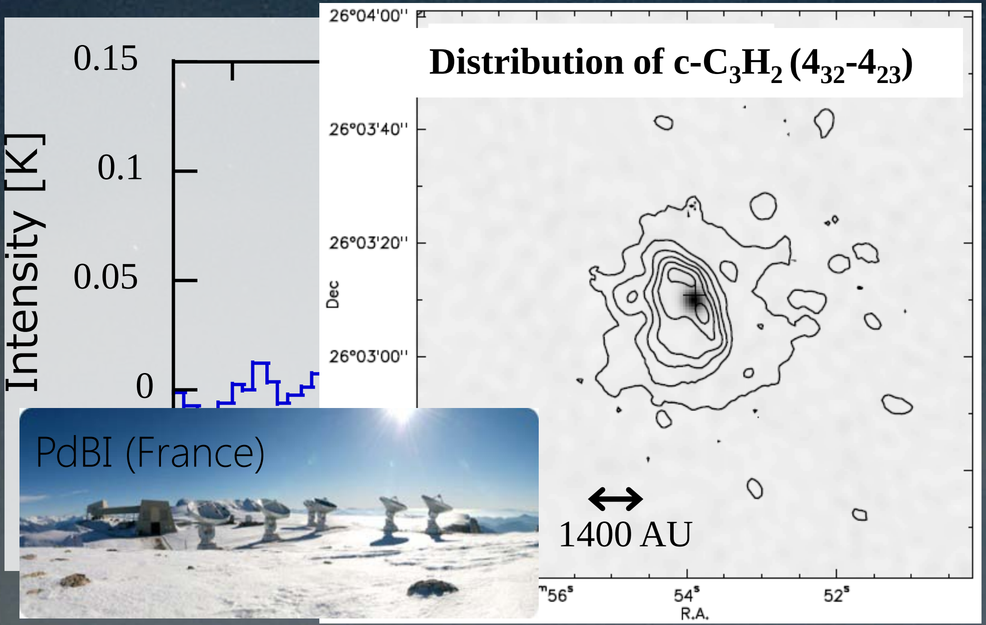
$HCOOCH_3$, CH_3OCH_3, C_2H_5CN, etc.
Hot Corino Chemistry

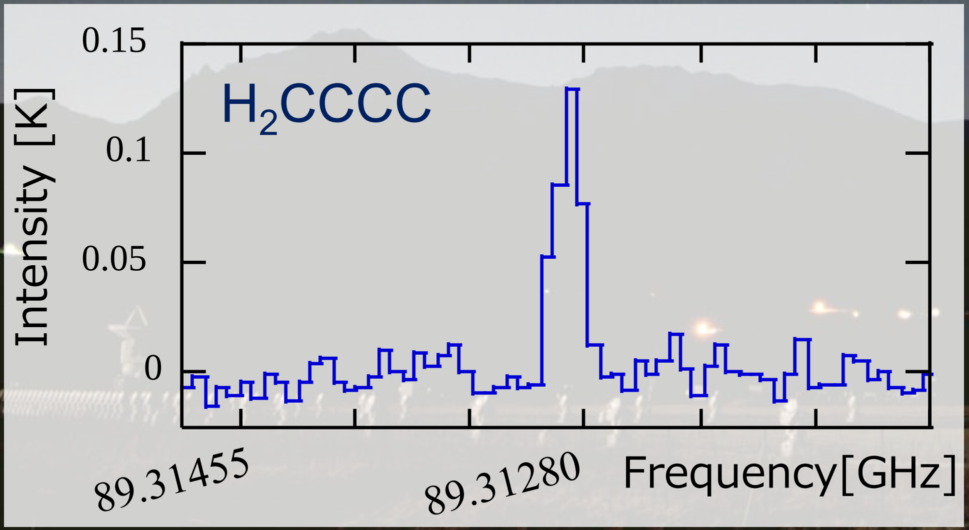
Detections of COMs in
NGC1333IRAS4A,
NGC1333IRAS4B,
& NGC1333IRAS2A.
Similar evolutionally stage
(e.g. Sakai et al. 2006, PASJ, 58, L15)

Existence of COMs in protostellar envelopes is a general phenomenon?

Photo: IRAM 30 m (Spain)

Discovery of WCCC in L1527





C_2H, $c\text{-}C_3H$, $l\text{-}C_3H$, $c\text{-}C_3H_2$, $l\text{-}C_3H_2$, C_4H, C_4H^-, C_4H_2, C_5H, C_6H, C_6H_2, C_6H^-, HC_3N, HC_5N, HC_7N, HC_9N, C_2O, C_3O, etc.

Evaporation of CH_4 from grain mantles (> 25 K)

$CH_4 + C^+ \rightarrow C_2H_3^+ + H$

$C_2H_3^+ + e$

$\rightarrow C_2H + H + H$

$\rightarrow$ - - - -

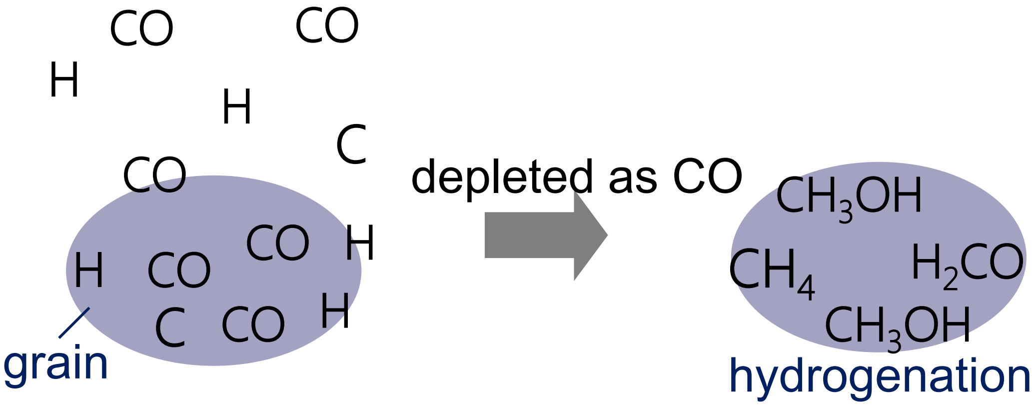
Warm Carbon-Chain Chemistry (WCCC)

Photo: NRO 45 m (Japan)

(e.g. Sakai et al. 2008, ApJ, 672, 372; Sakai et al. 2010, ApJ, 722, 1633)

Origin of the Chemical Diversity

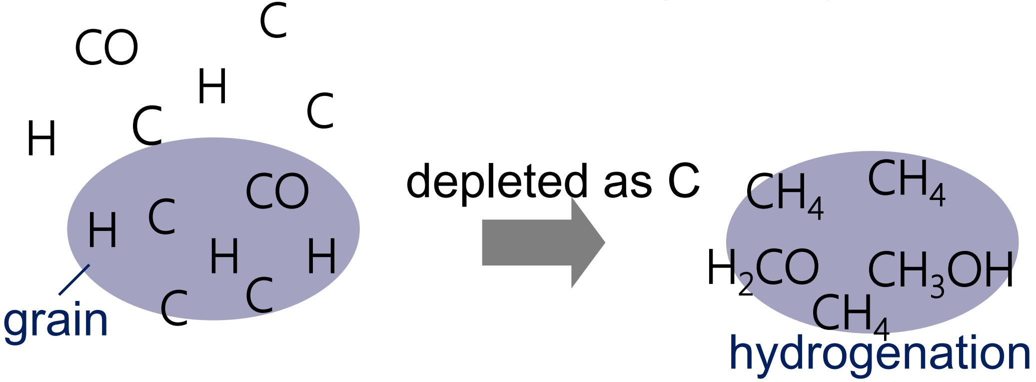
Long starless phase (~10^6 yr, starting time of the collapse: late)



Hot Corino

Saturated COMs
($HCOOCH_3$, etc.)

Short starless phase (~10^5 yr, starting time of the collapse: early)



WCCC

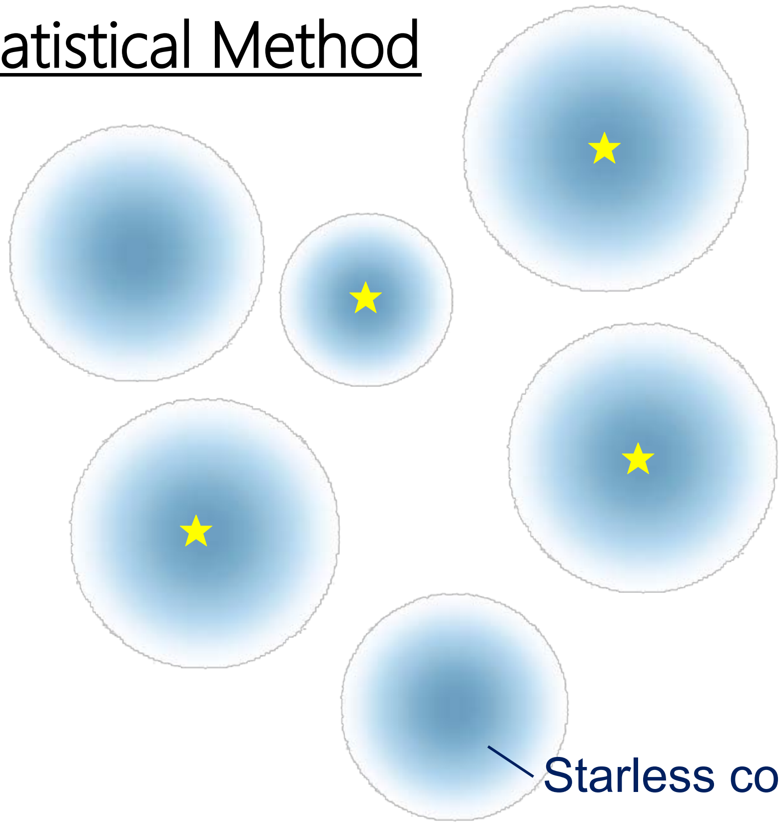
Unsaturated COMs
(Carbon-Chains)

(Sakai & Yamamoto 2013, Chem. Rev., 113, 8981)

Impact on Star Formation Studies

How long is the starless core phase?

Statistical Method

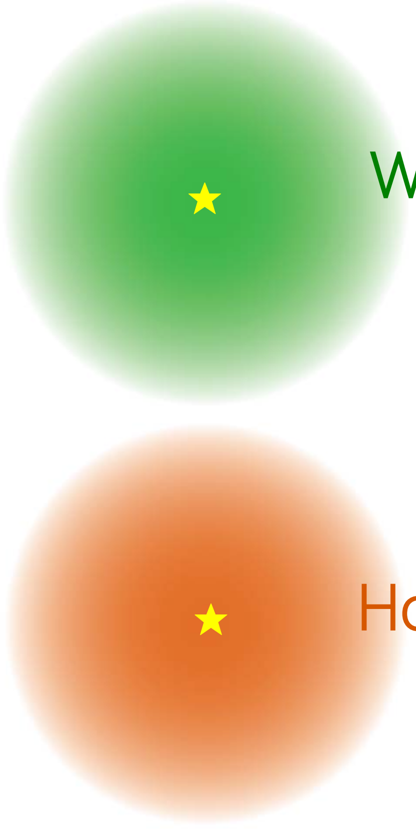


Starless core

$N(\text{Starless}) \propto \tau_{\text{starless}}$

$N(\text{Protostar}) \propto \tau_{\text{protostar}}$

Chemical Method



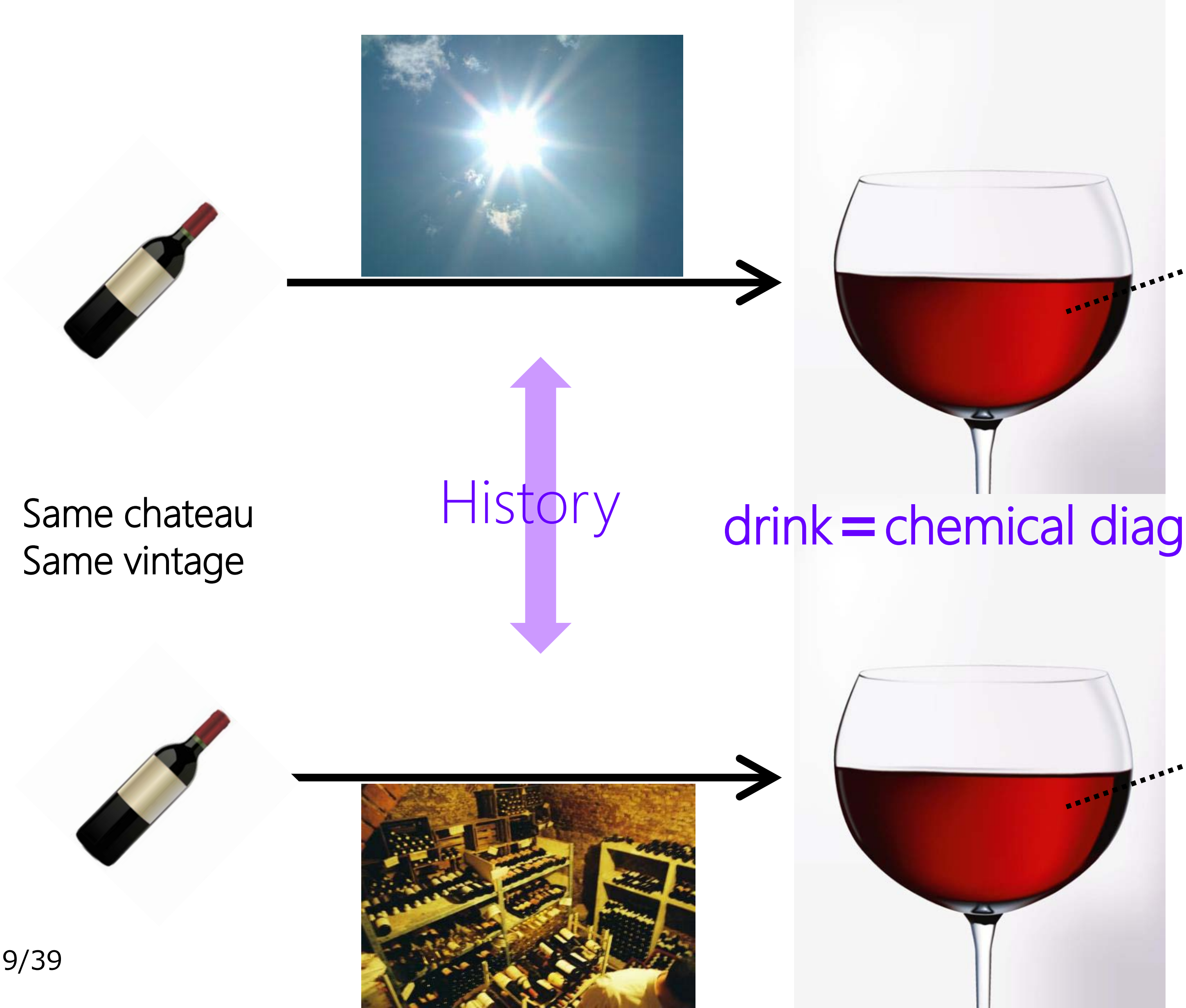
WCCC

→ ~10^5 yr

Hot Corino

→ ~10^6 yr

Chemical Diagnostics of Wine



Temperature
Density

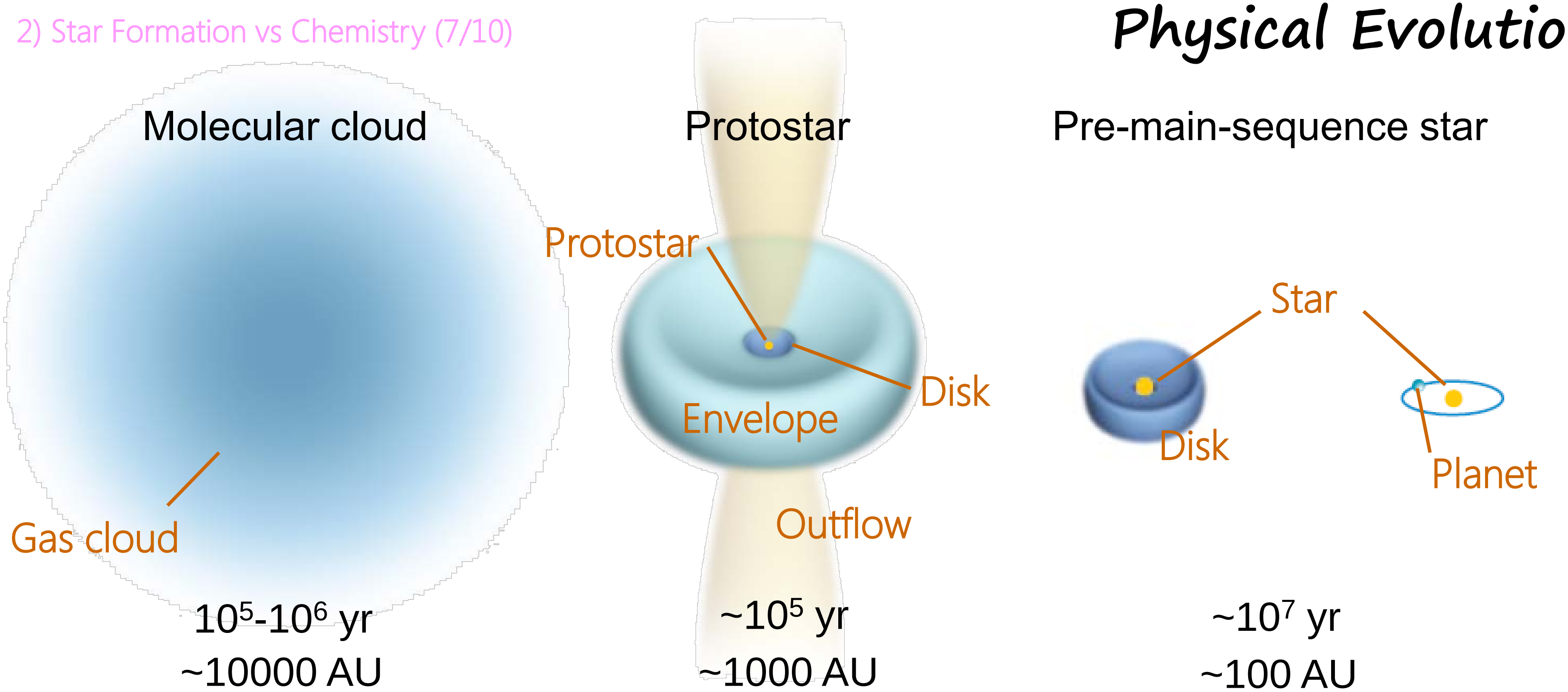
Same chateau
Same vintage

History

drink = chemical diagnostics!

Temperature
Density

Physical Evolution



Molecular cloud

Protostar

Pre-main-sequence star

Gas cloud

Protostar

Envelope

Disk

Outflow

Star

Disk

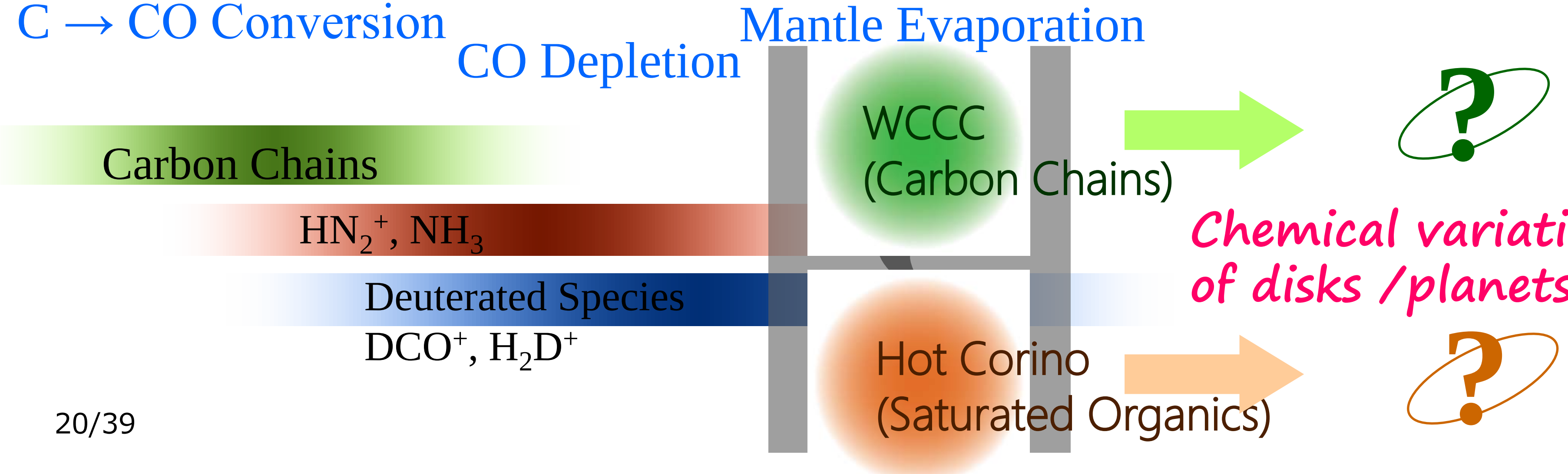
Planet

10^5-10^6 yr
~10000 AU

~10^5 yr
~1000 AU

~10^7 yr
~100 AU

Chemical Evolution



C → CO Conversion

CO Depletion

Mantle Evaporation

Carbon Chains

HN_2^+, NH_3

Deuterated Species
DCO^+, H_2D^+

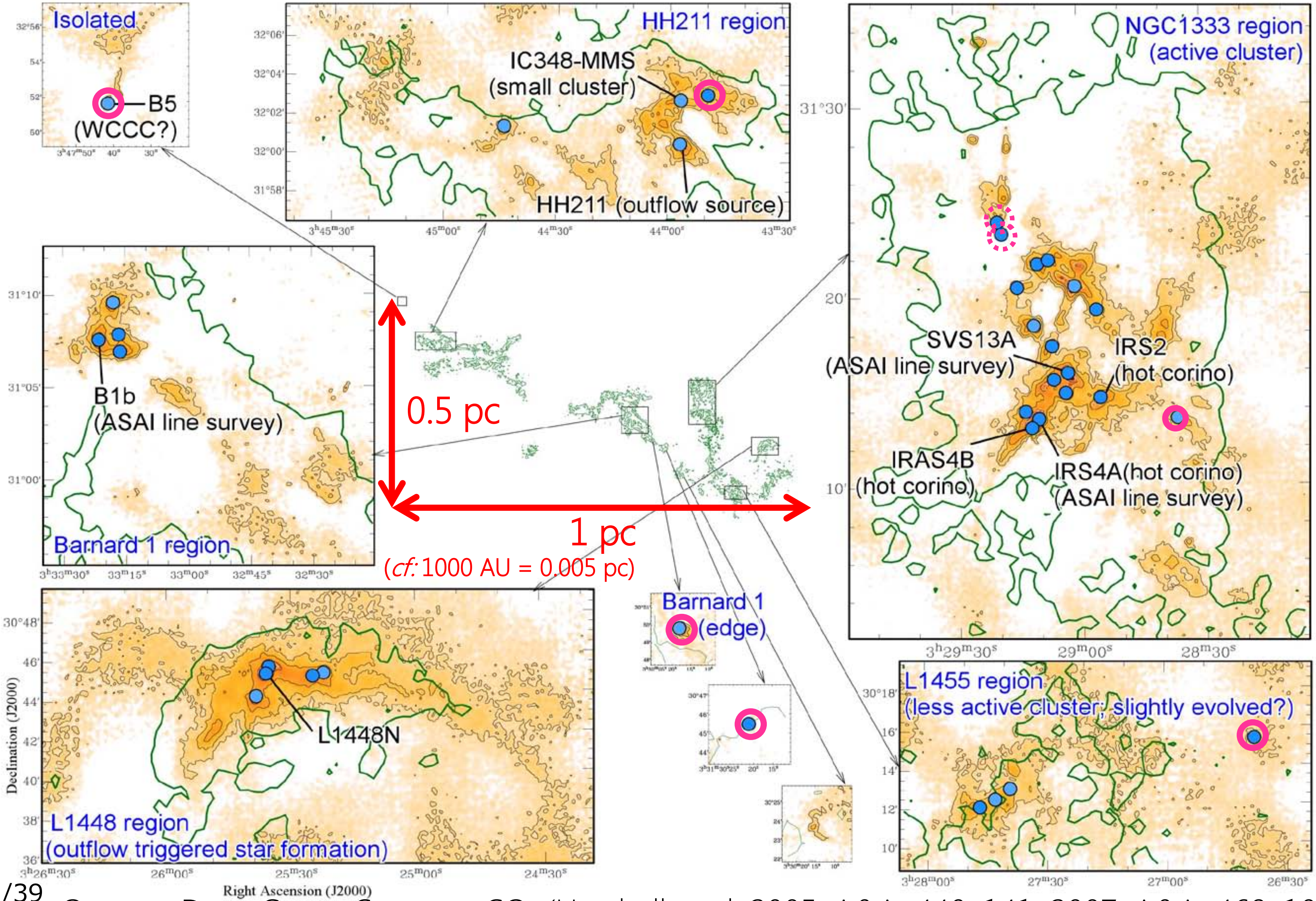
WCCC
(Carbon Chains)

Hot Corino
(Saturated Organics)

Chemical variation of disks / planets?

High CCH/CH_3OH ratio → ○

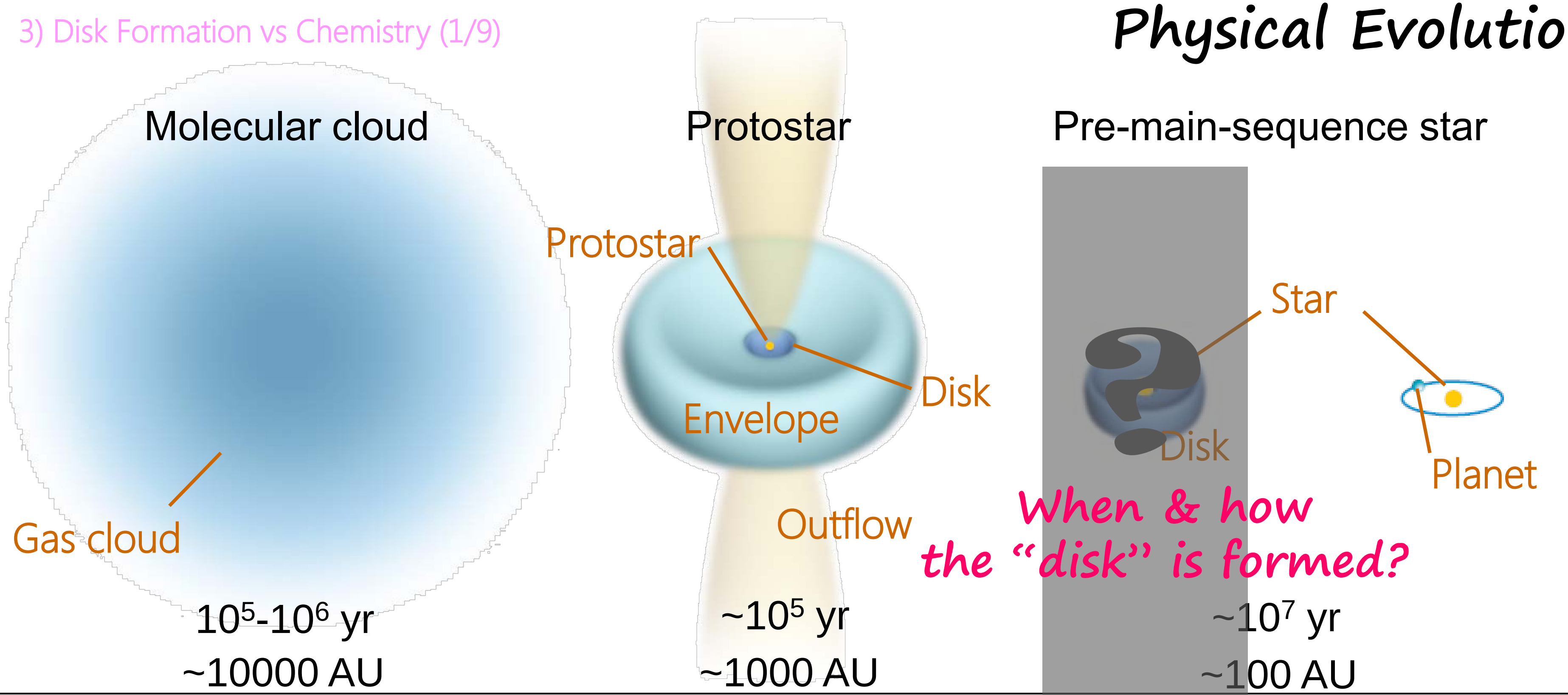
Perseus Molecular Cloud Complex



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

3) Disk Formation vs Chemistry (1/9)

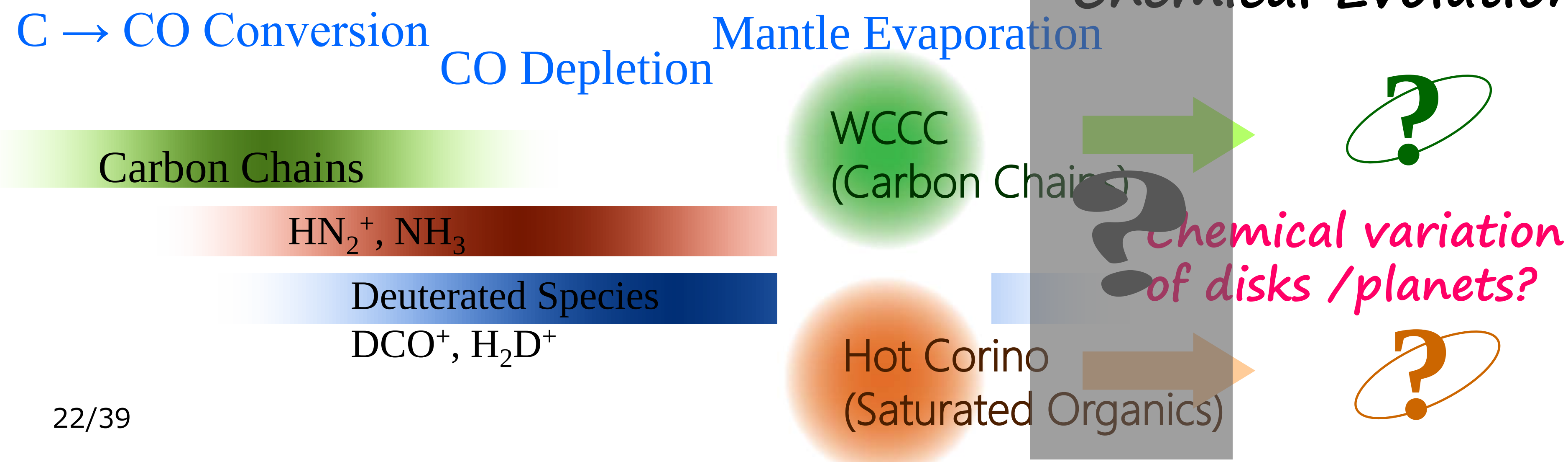
Physical Evolution



When & how the "disk" is formed?

Molecular cloud	Protostar	Pre-main-sequence star
10^5-10^6 yr	~10^5 yr	~10^7 yr
~10000 AU	~1000 AU	~100 AU

Chemical Evolution



Chemical variation of disks / planets?

ALMA (Atacama Large Millimeter/sub-millimeter Array

High angular resolution
1″ → <0.1″

High sensitivity
100 hours → 10 min.

Altitude: 5000 m

3 mm - 400 μm
(84 - 940 GHz)

66 antennae in total

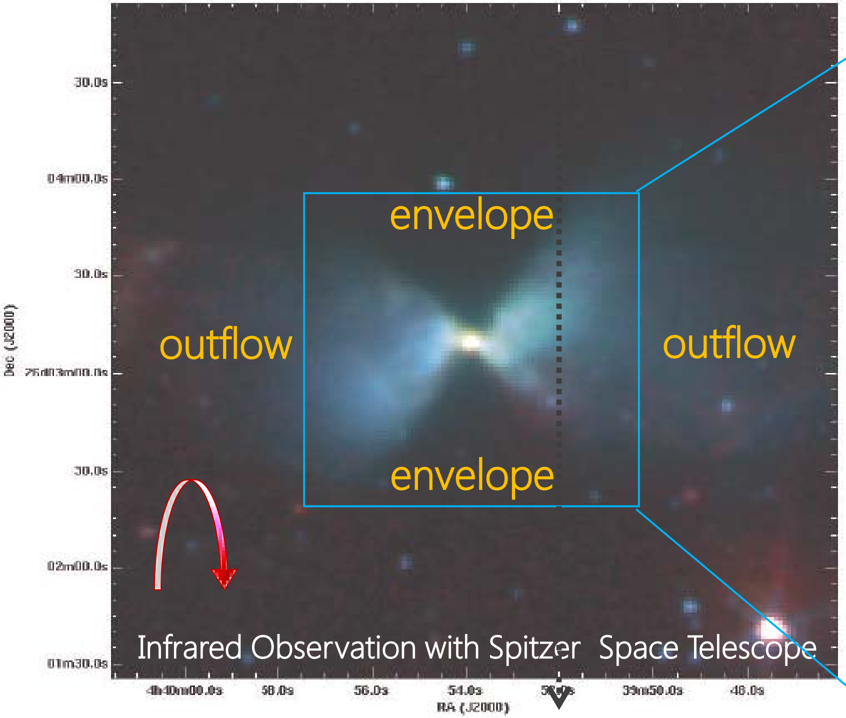
2011, partial operation with 16 antennae started
Europe, North America, and East Asia in cooperation with Chile

Resolving Disk-Forming Region with ALMA

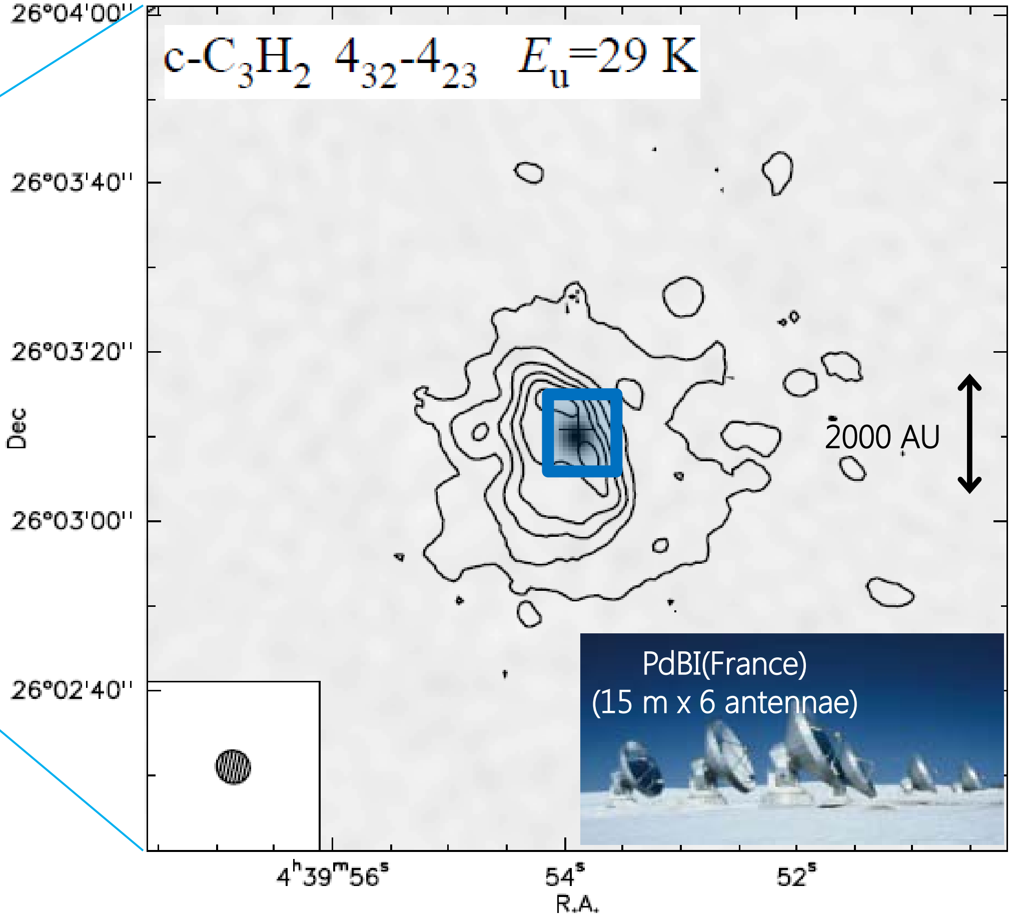
WCCC Source L1527

1AU = Distance between the Sun & the Earth

◆1000 AU Scale



(Tobin et al. 2008, ApJ, 679, 1364)



(Sakai et al. 2010, ApJ, 722, 1633)

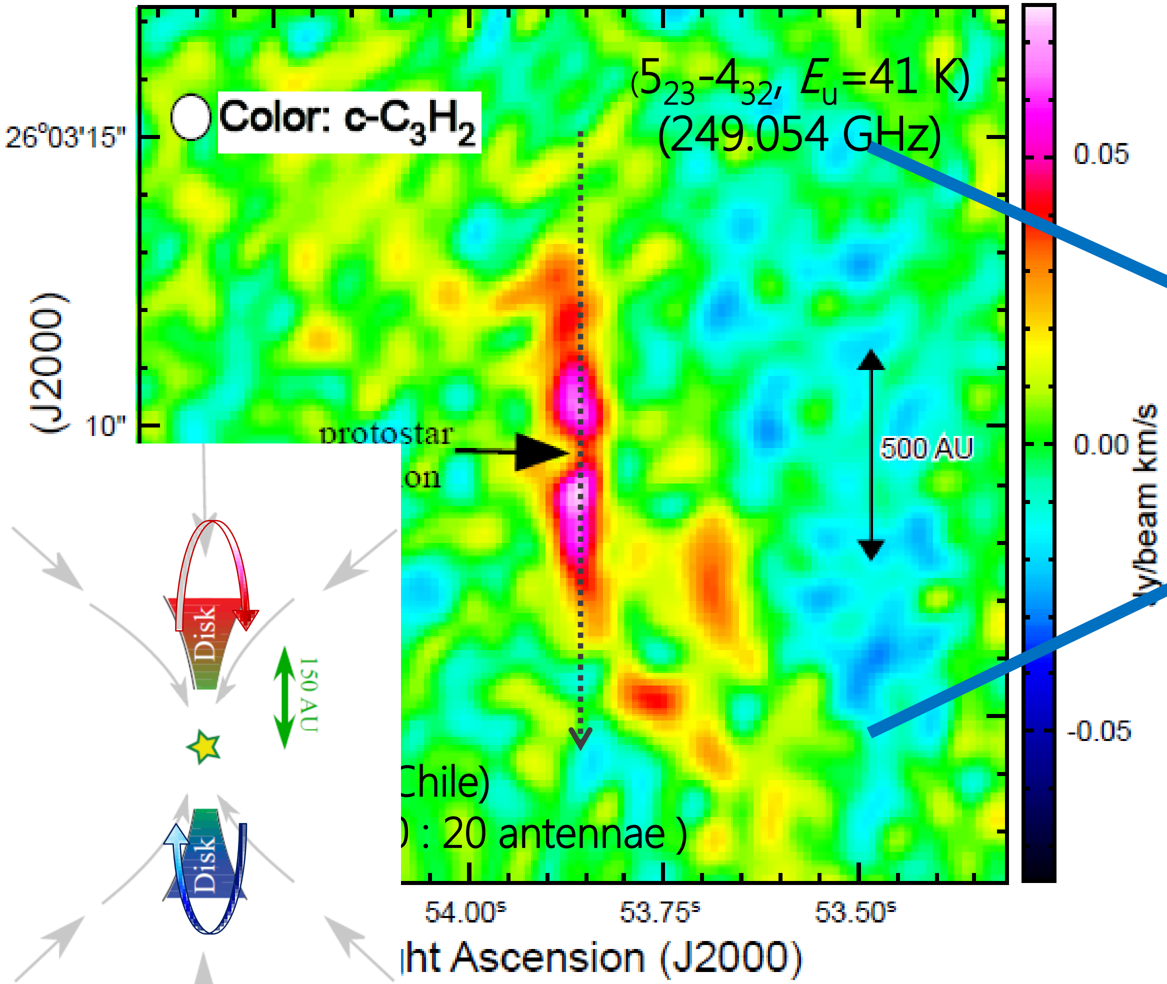
Resolving Disk-Forming Region with ALMA

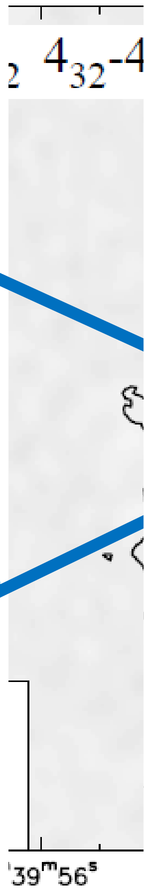
WCCC Source L1527

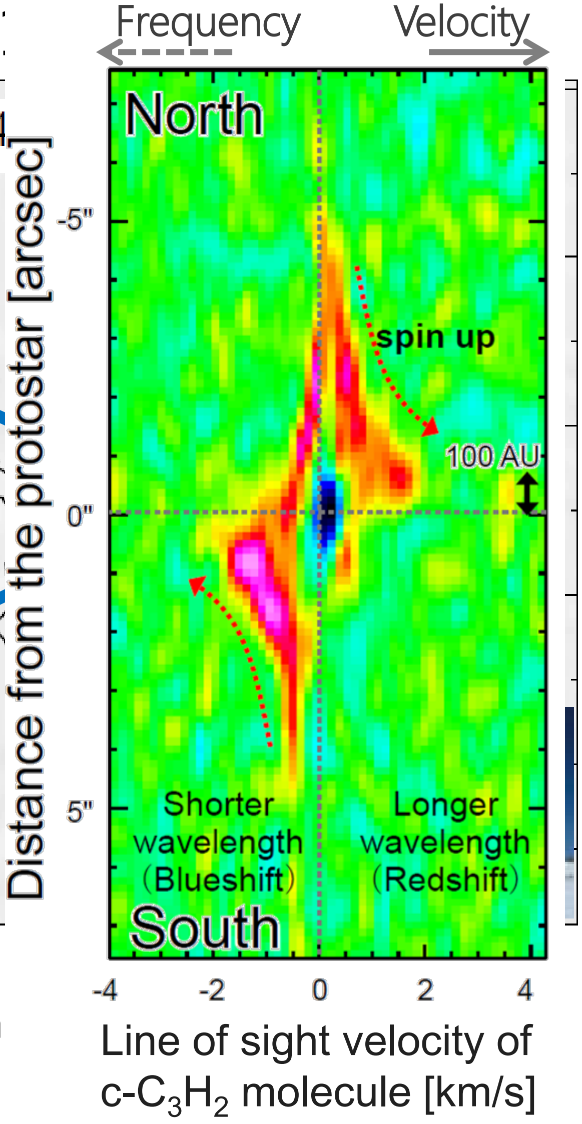
1AU = Distance between the Sun & the Earth

◆100 AU Scale

◆





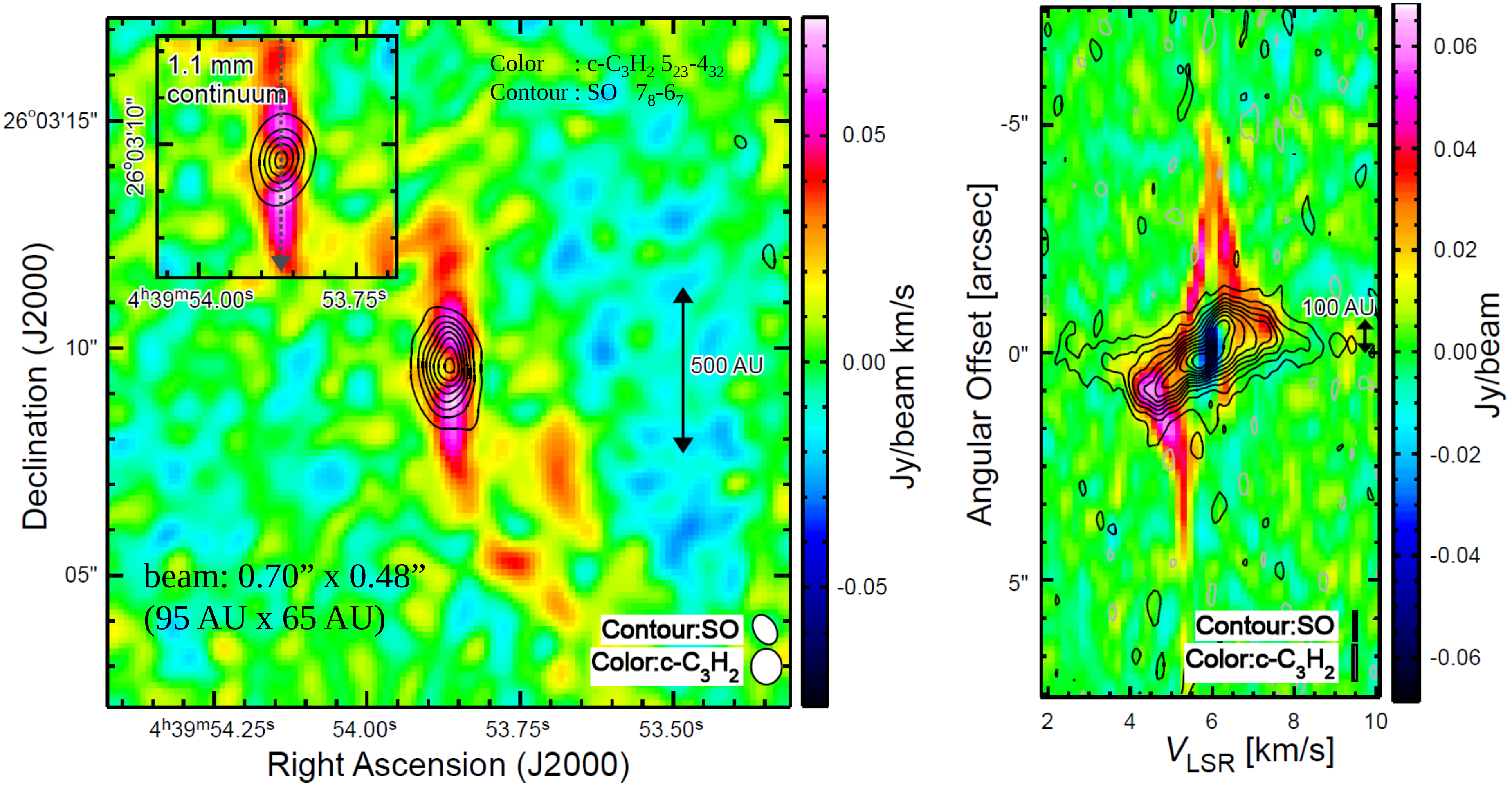


(Sa

(Sakai et al. 2014, Nature, 507, 78)

SO Distribution in L1527

~ Enhanced at r=100 AU ~

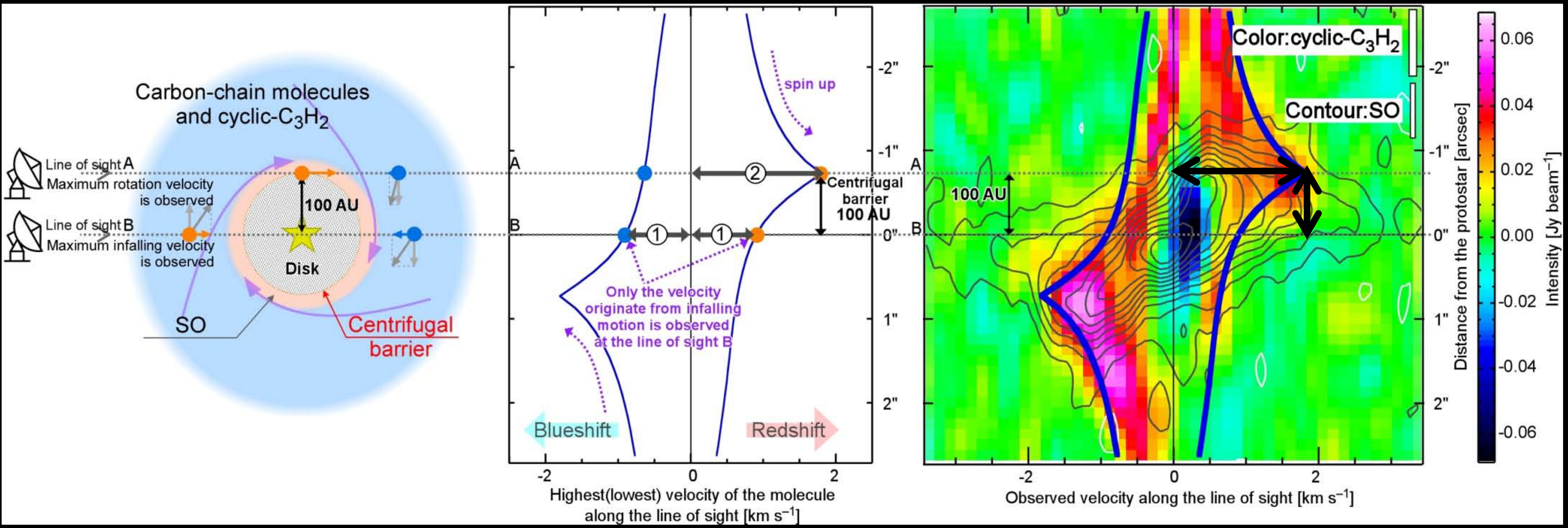


T_{ex} of SO (>60 K) is higher than T_{ex} of c-C_3H_2 (~30 K)

(Sakai et al. 2014, Nature, 507, 78)

Discovery of the "Centrifugal Barrier"

(Sakai et al. 2014, Nature, 507, 78)

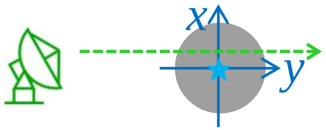


Angular momentum & energy conservation

$$\frac{m}{2}\left(V_{rot}^2+V_{infall}^2\right)=\frac{GMm}{r}$$

$$mrV_{rot}=L$$

$$V_{observed}=V_{rot}\frac{x}{r}+V_{infall}\frac{y}{r}$$



$$\left(V_{rot}=\left(\frac{L}{m}\right)\frac{1}{r},\quad V_{infall}=\sqrt{\frac{2GM}{r}-V_{rot}^2}\right)$$

Parameter: M, L/m

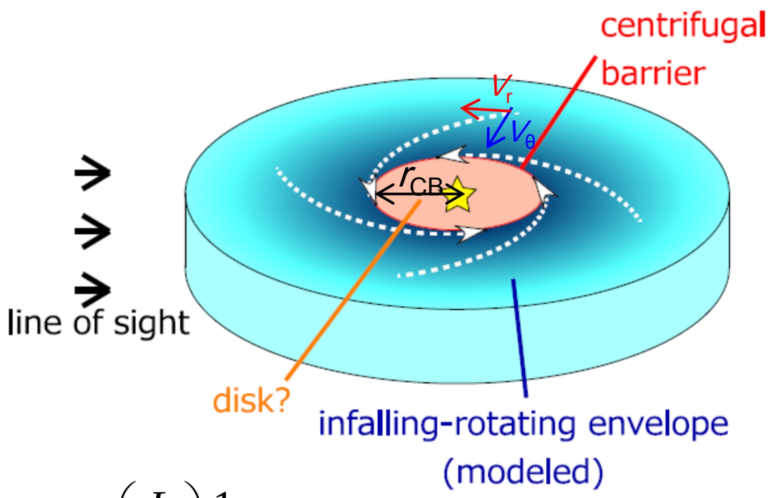
@Centrifugal barrier(CB)
All the kinetic energy is used for rot. motion

$$V_{rot}^{max}=2GM\frac{m}{L}\qquad r_{CB}=\frac{1}{2GM}\left(\frac{L}{m}\right)^2$$

r_{CB} = 100±20 AU, M = 0.18±0.02 $M_\odot$

Discovery of the "Centrifugal Barrier"

Toy model for the Infalling rotating envelope

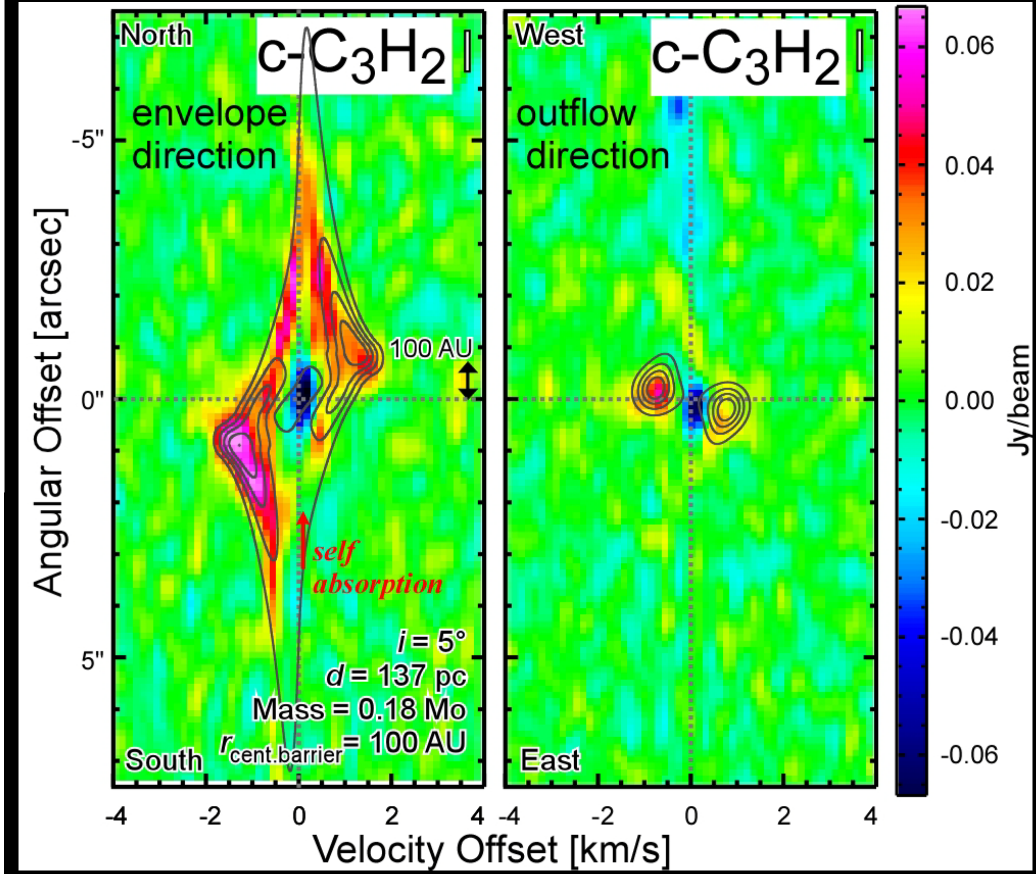


$$V_{rot} = \left(\frac{L}{m}\right)\frac{1}{r}$$

$$V_{infall} = \sqrt{\frac{2GM}{r} - V_{rot}^2}$$

$$\boxed{r_{CB} = \frac{1}{2GM}\left(\frac{L}{m}\right)^2}$$

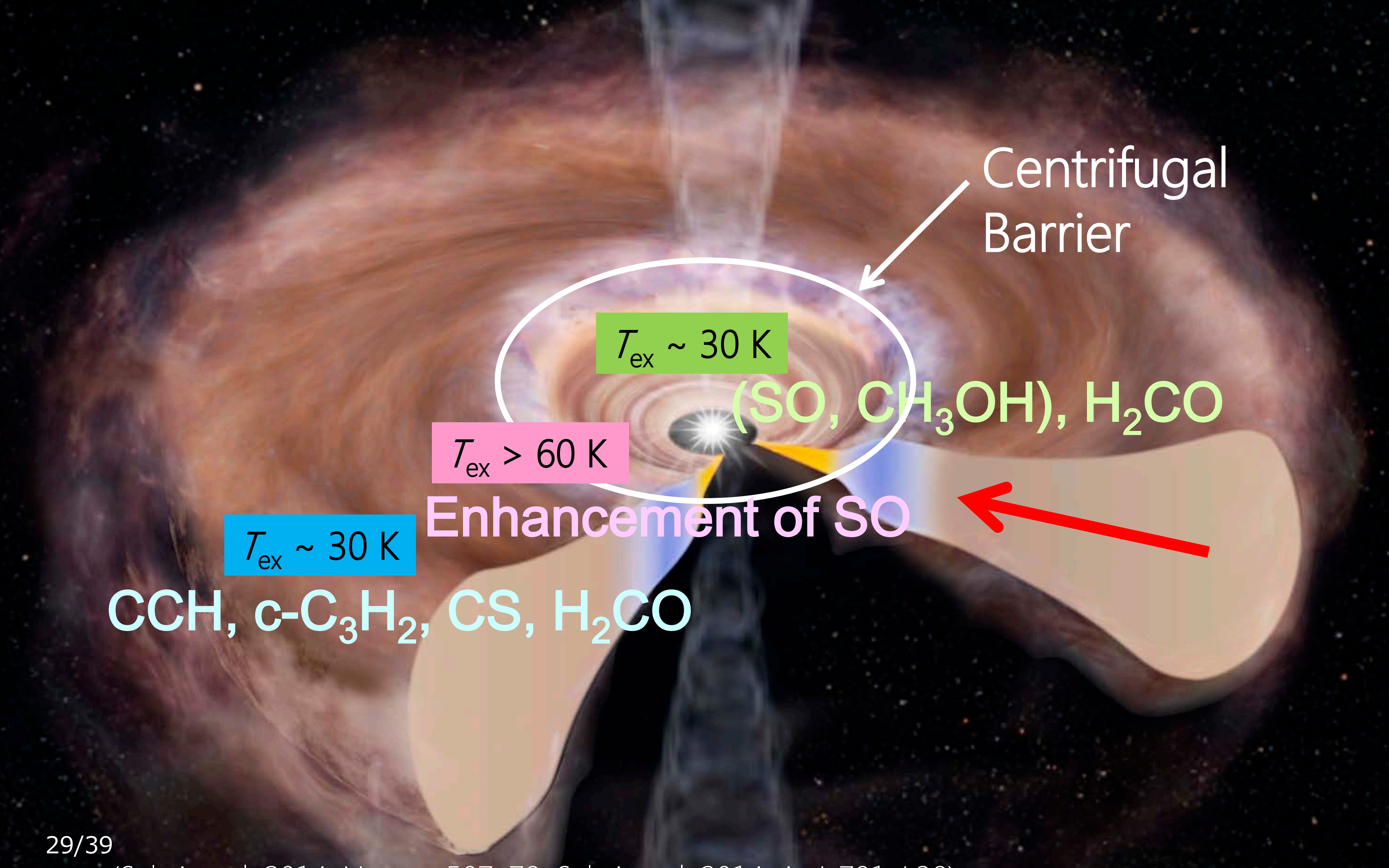
$$\boxed{r_{CB}, M \rightarrow L/m \rightarrow V_{rot}(r), V_{infall}(r)}$$



Assumed:
i =5°, *d* =137 pc, beam size(for each line),
linewidth of 0.5 km/s, density profile $r^{-1.5}$,
r_{out}=1000 AU, thickness=20 AU

(Sakai et al. 2014, ApJ, 791, L38)
(Oya, Sakai et al. 2014, ApJ, 795, 152)

Drastic Chemical Change at CB



Centrifugal Barrier

T_{ex} ~ 30 K

(SO, CH_3OH), H_2CO

T_{ex} > 60 K

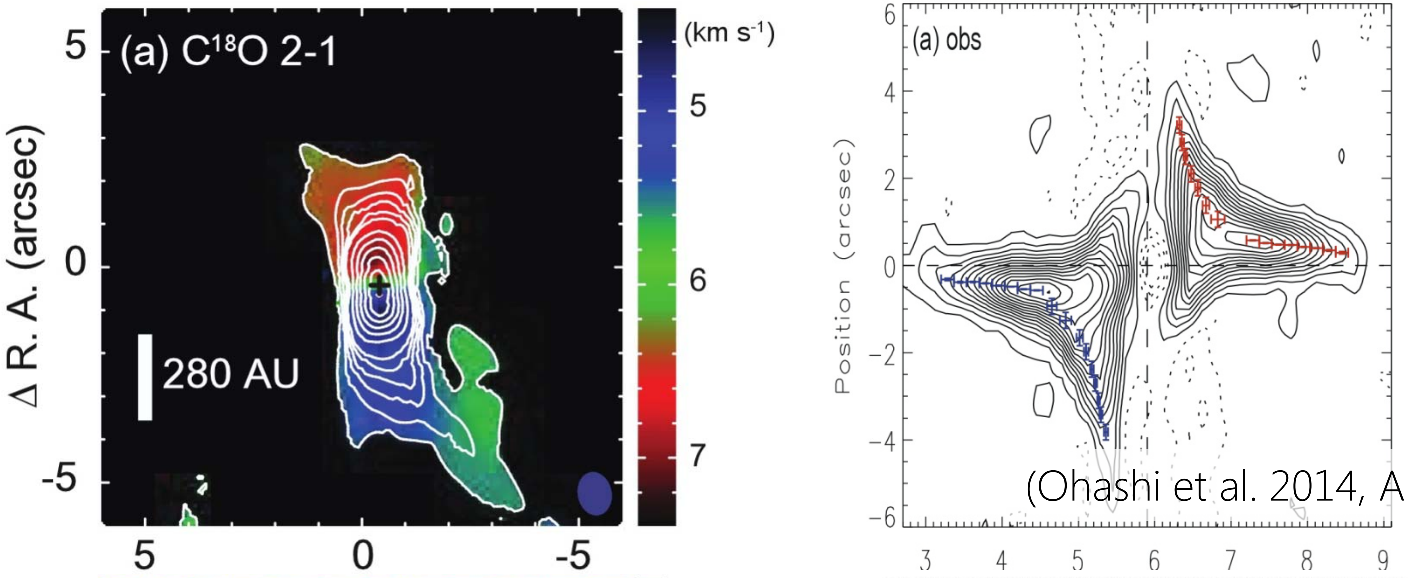
Enhancement of SO

T_{ex} ~ 30 K

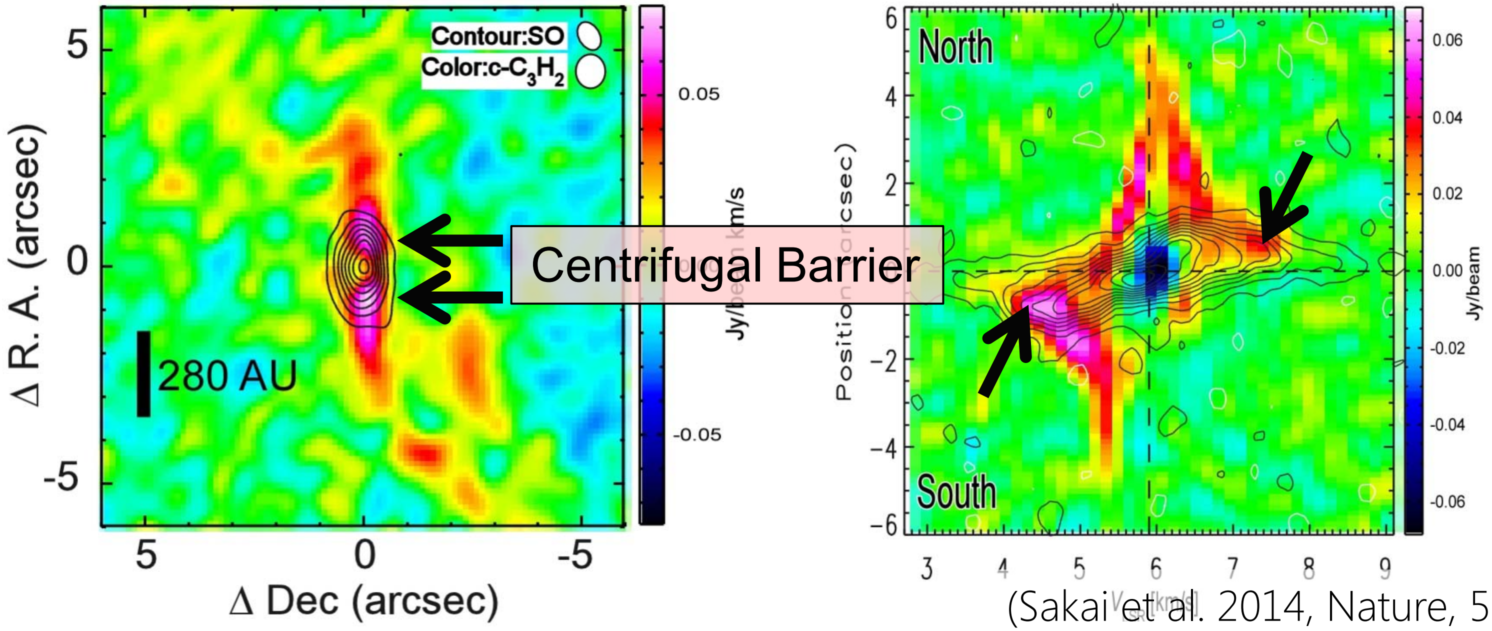
CCH, c-C_3H_2, CS, H_2CO

(Sakai et al. 2014, Nature, 507, 78; Sakai et al. 2014, ApJ, 791, L38)

Chemistry Highlights the Physical Change



(Ohashi et al. 2014, ApJ, 796, 131)



Centrifugal Barrier

(Sakai et al. 2014, Nature, 507, 78)

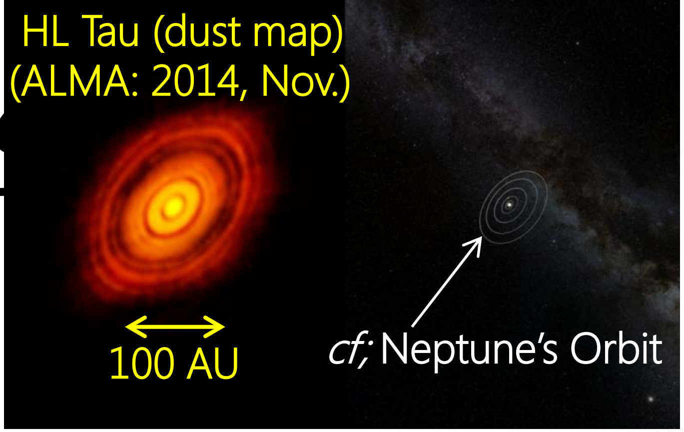
Physical Implication of Centrifugal Barrier

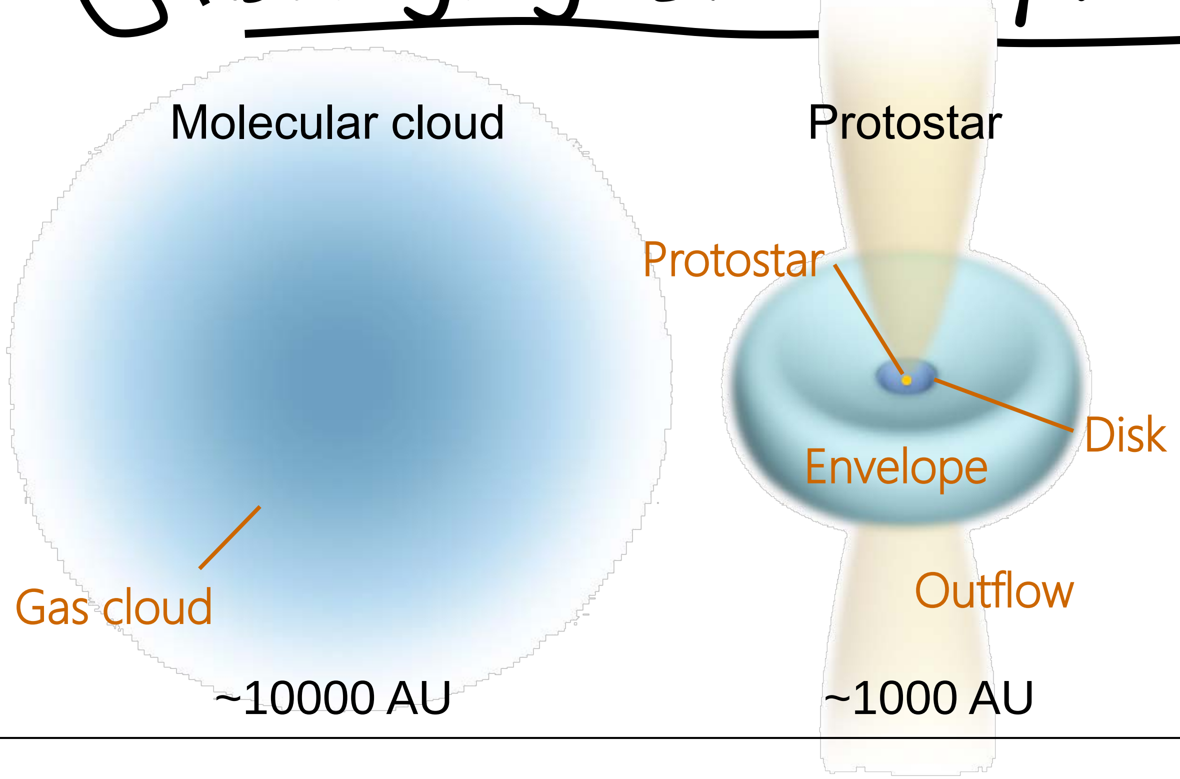
--First observational identification--

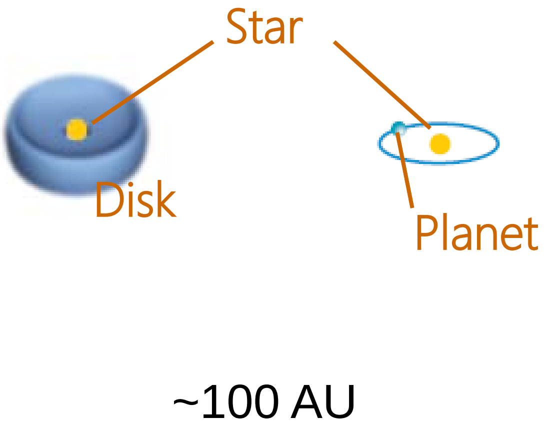
- A key to disk formation
  --Is CB the outer most part of disk?
  --When & how the disk is formed?

- Angular momentum problem
  --How the materials are delivered beyond CB?
  --Any relation to molecular outflow?

Bridging ISM and plan



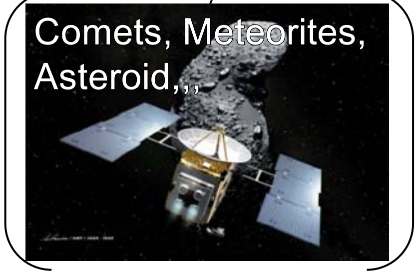




Radio Astronomy
(WCCC vs Hot corino)

ALMA

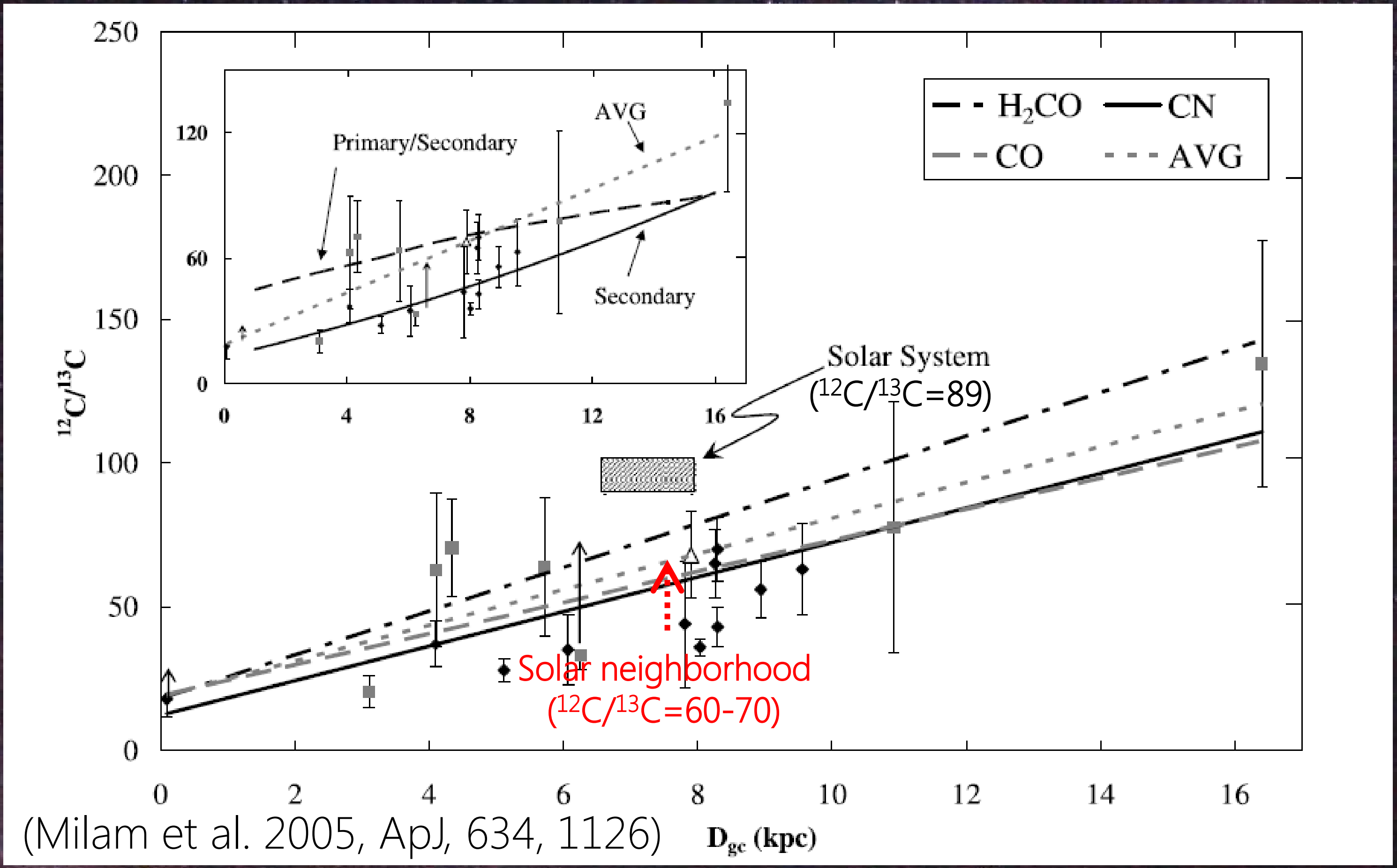
Planetary Science



From 0.5 arcsec to 0.05 arcsec
(100 AU to 10 AU)

→ ^{13}C isotopic species as a new tracer?

$^{12}C/^{13}C$ Ratio in Our Galaxy

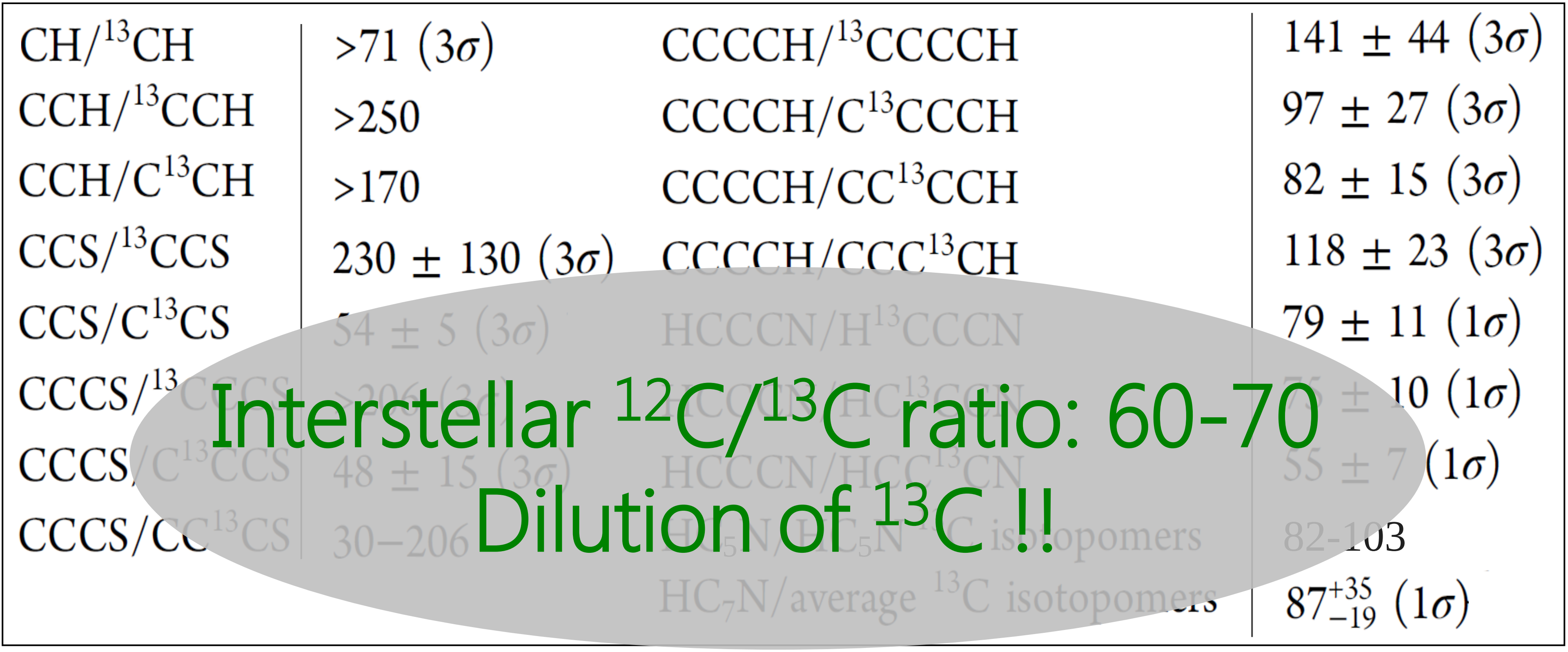


(Milam et al. 2005, ApJ, 634, 1126)

Photo: Cygnus

$^{12}C/^{13}C$ ratios in Molecules

TMC-1(Starless cloud)

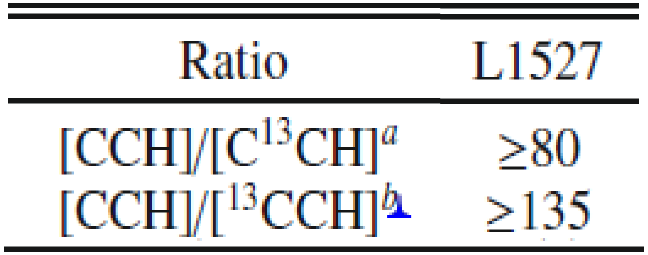


$CH/^{13}CH$	>71 (3σ)	$CCCCH/^{13}CCCCH$	141 ± 44 (3σ)
$CCH/^{13}CCH$	>250	$CCCCH/C^{13}CCCH$	97 ± 27 (3σ)
$CCH/C^{13}CH$	>170	$CCCCH/CC^{13}CCH$	82 ± 15 (3σ)
$CCS/^{13}CCS$	230 ± 130 (3σ)	$CCCCH/CCC^{13}CH$	118 ± 23 (3σ)
$CCS/C^{13}CS$	54 ± 5 (3σ)	$HCCCN/H^{13}CCCN$	79 ± 11 (1σ)
$CCCS/^{13}CCCS$	>206 (3σ)	$HCCCN/HC^{13}CCN$	75 ± 10 (1σ)
$CCCS/C^{13}CCS$	48 ± 15 (3σ)	$HCCCN/HCC^{13}CN$	55 ± 7 (1σ)
$CCCS/CC^{13}CS$	30–206	HC_5N/HC_5N ^{13}C isotopomers	82-103
		HC_7N/average ^{13}C isotopomers	87^{+35}_{-19} (1σ)

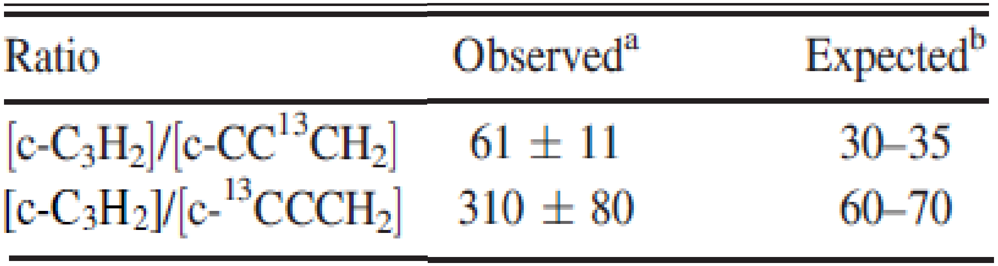
Interstellar $^{12}C/^{13}C$ ratio: 60-70

Dilution of ^{13}C !!

L1527



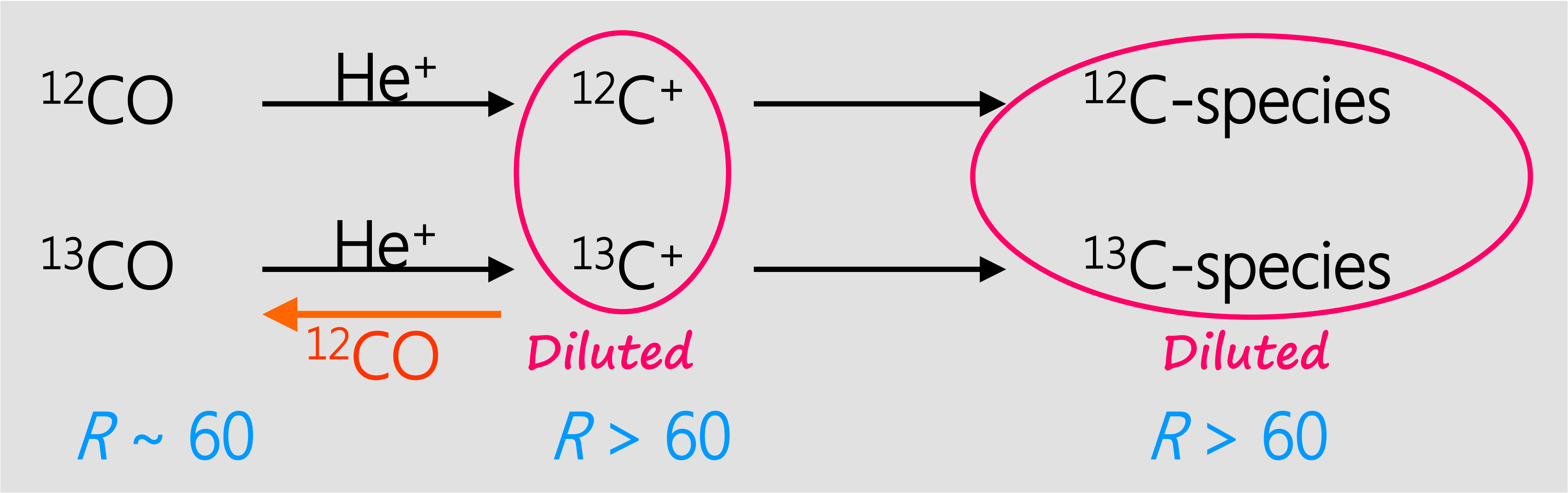
Ratio	L1527
$[CCH]/[C^{13}CH]$[a]	≥80
$[CCH]/[^{13}CCH]$[b]	≥135



Ratio	Observed[a]	Expected[b]
$[c\text{-}C_3H_2]/[c\text{-}CC^{13}CH_2]$	61 ± 11	30–35
$[c\text{-}C_3H_2]/[c\text{-}^{13}CCCH_2]$	310 ± 80	60–70

(*e.g.* Sakai et al. 2013, JPC, 117, 9831; Yoshida, Sakai et al. 2015, ApJ, 807, 66)

Origin of the ^{13}C Dilution



$^{12}CO \xrightarrow{He^+} {}^{12}C^+ \longrightarrow {}^{12}$C-species

$^{13}CO \xrightarrow{He^+} {}^{13}C^+ \longrightarrow {}^{13}$C-species

$\xleftarrow{}$ ^{12}CO

Diluted

Diluted

R ~ 60

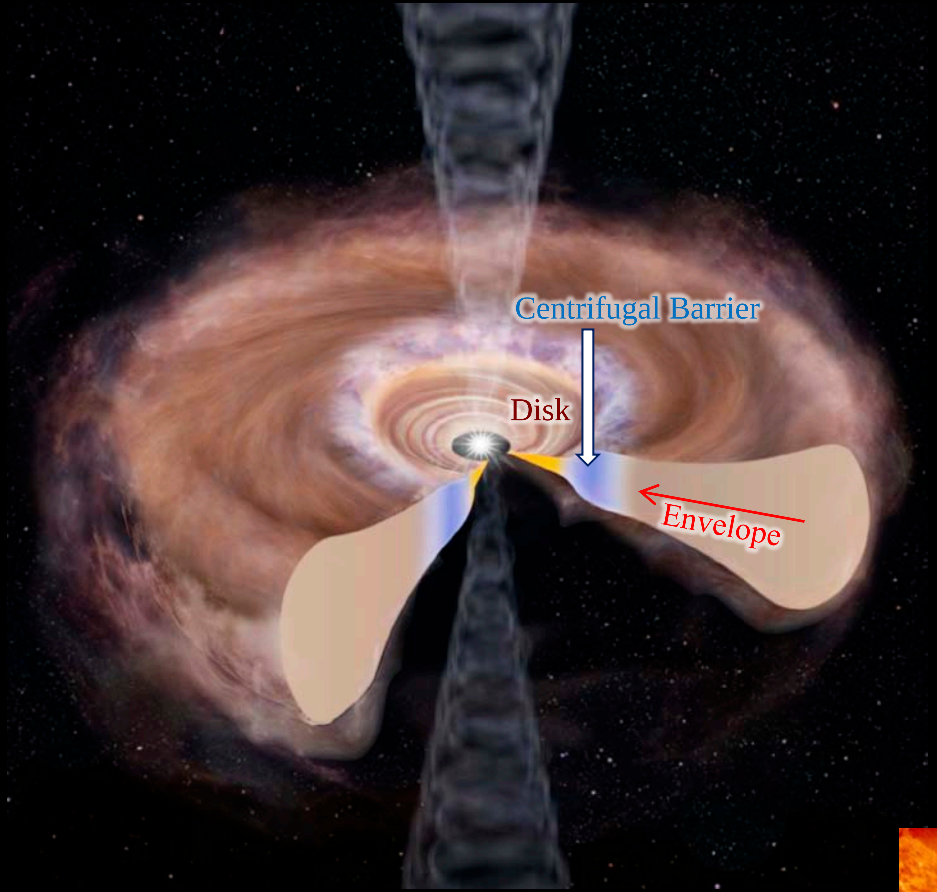
R > 60

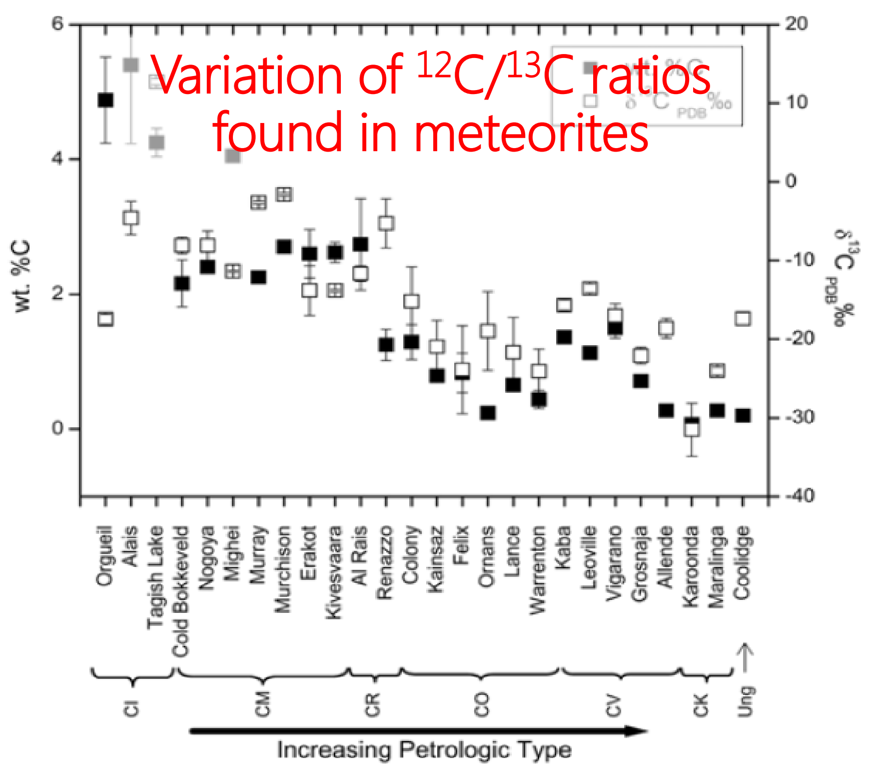
R > 60

$$^{13}C^+ + {}^{12}CO \rightarrow {}^{13}CO + {}^{12}C^+ + 35\ K$$

(*c.f.* Langer et al. 1984, ApJ, 277, 581)

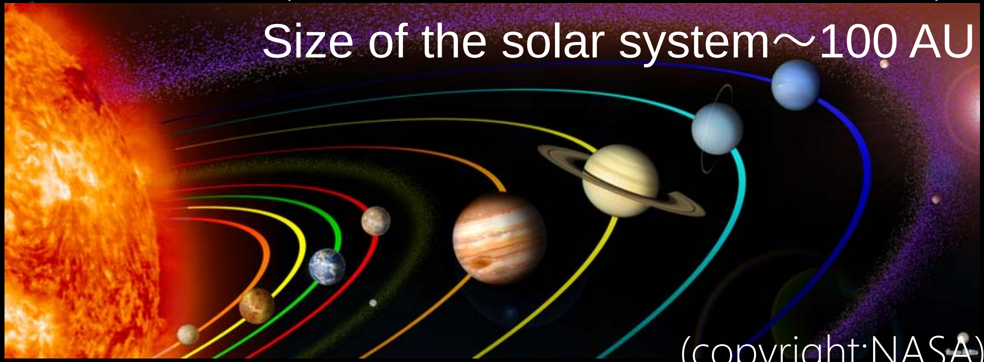
Tracing $^{12}C/^{13}C$ ratios in Disk Forming Regions





Variation of $^{12}C/^{13}C$ ratios found in meteorites

(Pearson et al. 2006, M&PS, 41, 1899)



Size of the solar system～100 AU

(copyright:NASA)

What type of molecules will be preserved on dust grains?

Why Chemistry ?

1) Molecular Cloud Formation

   Grav. Collapse, Compression, etc.
   (C/CO, CH, OH...)

2) Star Formation

   Different starting time of the collapse → Chemical Variation
   (Carbon-Chains & COMs)

3) Disk Formation

   Discovery of Centrifugal Barrier
   (CS, Carbon-Chains, SO...)

4) Toward Protoplanetary Disks & Planets

   Isotope ratios...?

Why Not Chemistry ??

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(Yamamoto Lab. Members)

(New Lab.@RIKEN From Apr. 2015)