

宇宙線 x 原始星円盤・原始惑星系円盤の 化学進化、ALMA観測による宇宙線電離率測定

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関連講演：高棹さん (星・惑星形成 & 原始惑星系円盤)、行方さん (中心星放射)

自己紹介

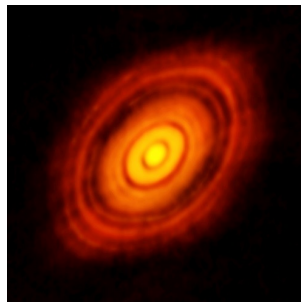


- ・天文学・宇宙物理学・惑星科学の研究者
京都大学・理(学部・修士・博士)
→オランダ🇳🇱・ライデン大学(海外学振PD)
→理化学研究所(基礎特研)→東京大学・天文(学振PD)
- ・2023.12-: 東京大学 理学系研究科 地球惑星科学専攻
地球惑星システム科学講座 助教
- ・中学生時に読んだ新書→宇宙や地球・生命の起源に興味を持つ
→理学部に進学

研究分野：星・惑星形成、原始惑星系円盤、アストロケミストリー
手法：理論モデル計算+観測 (アルマ望遠鏡など)



アルマ望遠鏡
(ALMA)



原始惑星系円盤
観測例

(ALMA partnership et al. 2015)

**太陽系や太陽系外の惑星はどのように作られたのか？
水や有機分子の起源、惑星にはどの様に供給されたのか？**

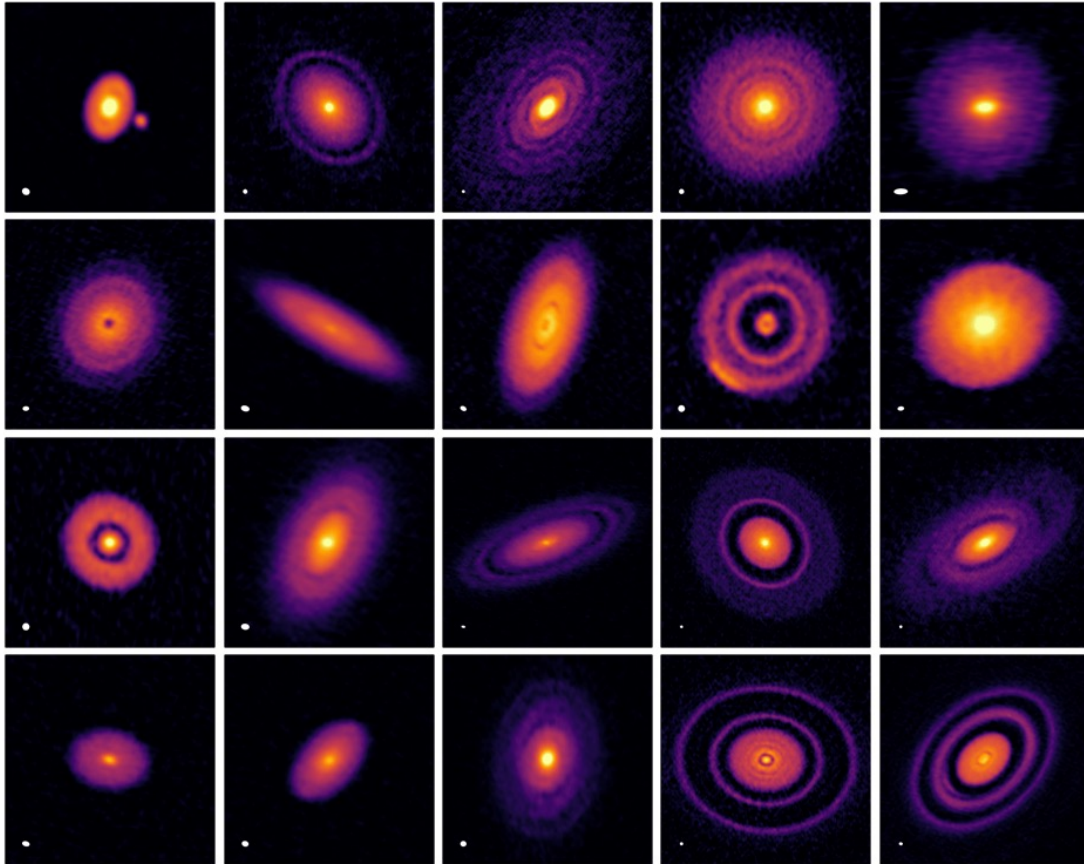
惑星科学・太陽系物質との比較議論・研究もさらに進めたい

High spatial resolution observations of disks with ALMA

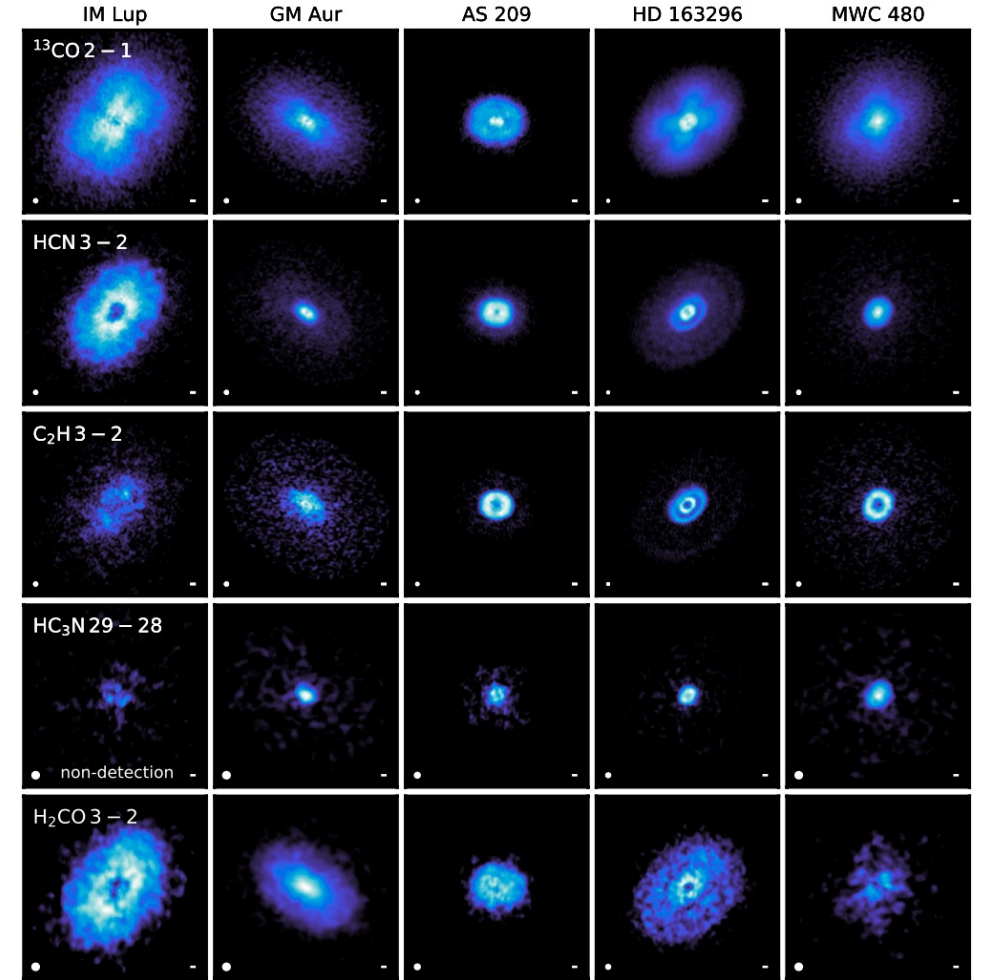
Dust emission (e.g., Andrews et al. 2018)
DSHARP



ALMA



Molecular gas MAPS



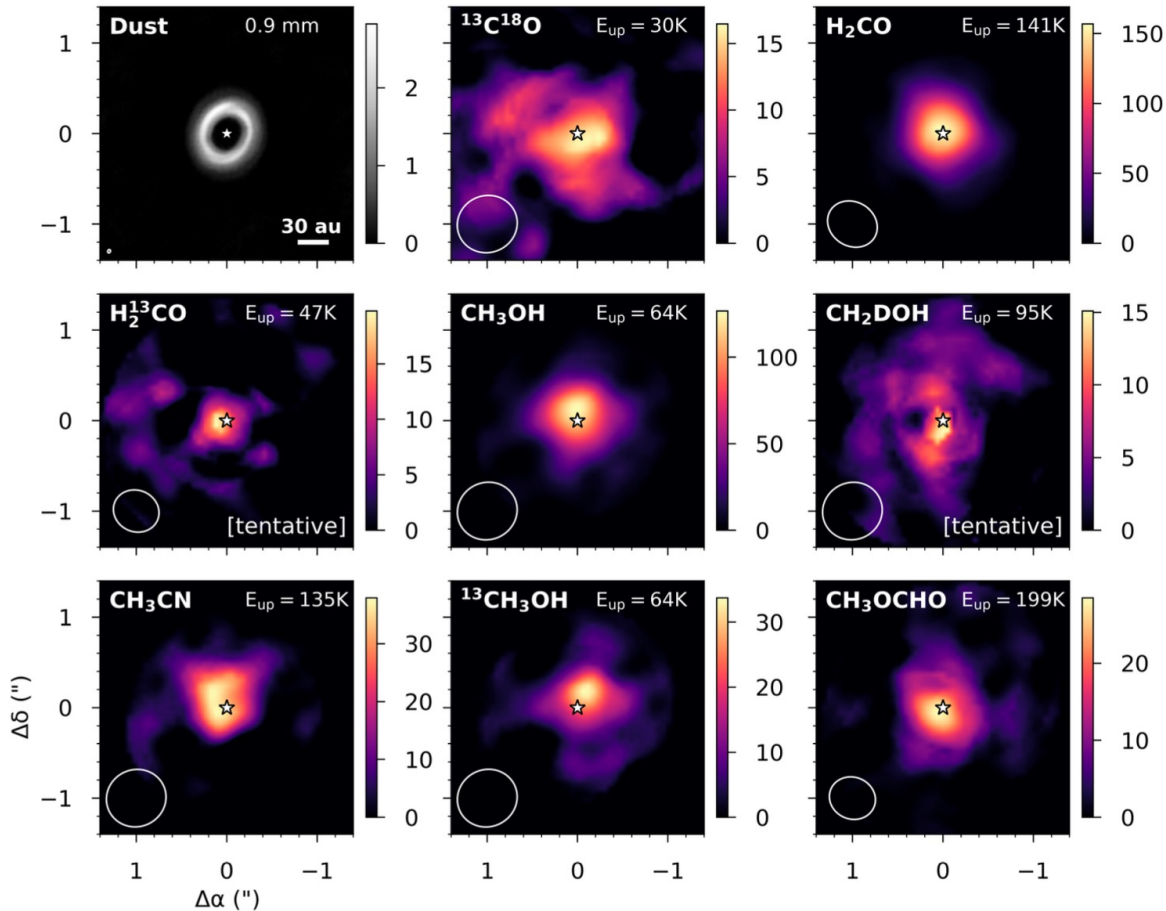
(e.g., Öberg et al. 2021)

Substructures (rings, gaps, spirals) are universal

ALMA (Atacama Large Millimeter/
submillimeter Array)

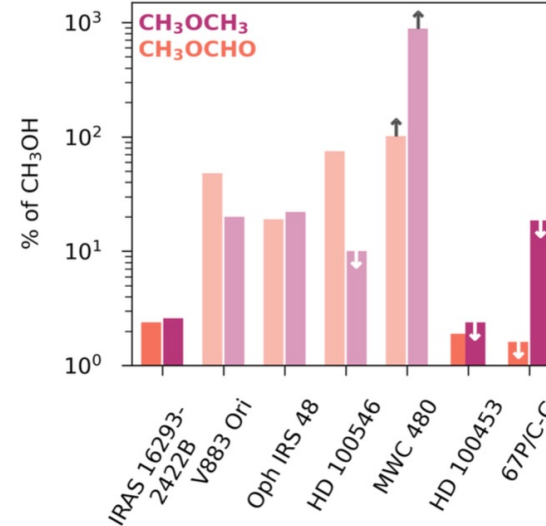
Complex organic molecules have been detected in disks

$T_{\text{snowline}}(\text{H}_2\text{O}) \sim T_{\text{snowline}}(\text{CH}_3\text{OH}) \sim 100\text{-}150\text{K}$

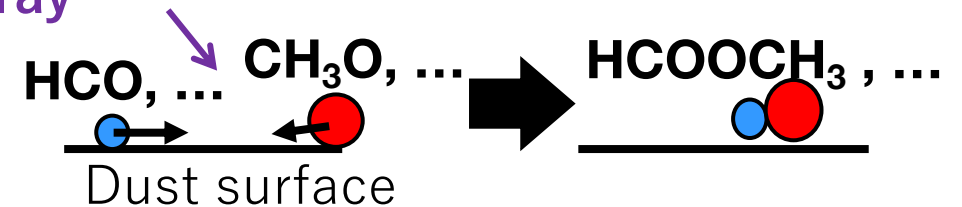


$T_{\text{rot}}(\text{CH}_3\text{OH}) \sim 200\text{ K}$

Herbig Ae disk
HD 100543



UV
Cosmic-ray
X-ray



Cosmic-ray ionization in disks are important for formation of complex organic molecules!



Alice S. Booth
(Harvard/CfA)

Y. Yamato
(PhD student in UTokyo)
→SPDR Fellow in RIKEN
(April 2025-)

Astrochemistry and star and planet formation

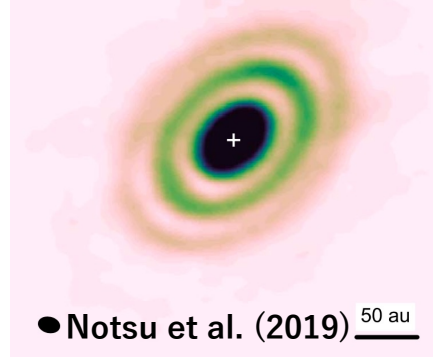
Molecular clouds



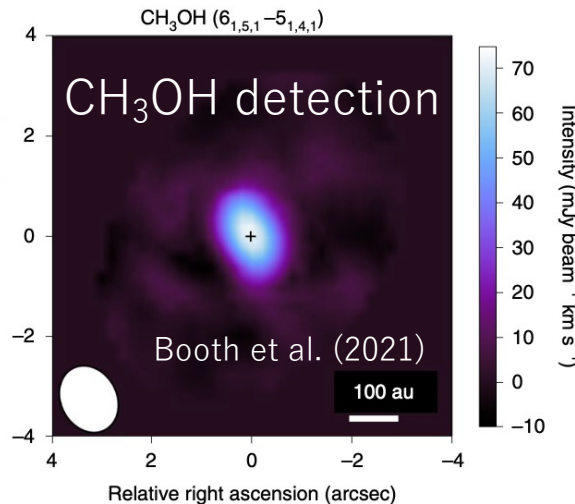
~99% gas
~1% dust

Protoplanetary disks

Dust substructures

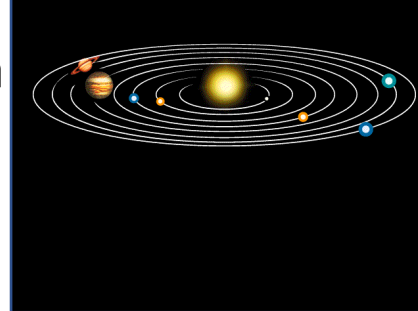


Dust growth



Planetary systems

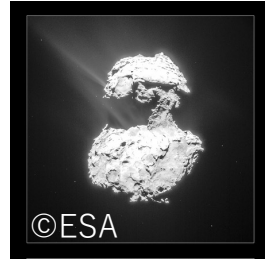
Many exoplanets have found.



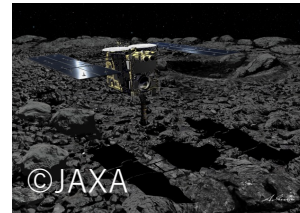
Planet formation



Comets



Primitive asteroids



Chemical evolution (including formation of organic molecules) proceeds along with dust evolution and formation of dust and gas substructures

What kind of / how much (complex) molecules are brought in various planets and primitive objects?

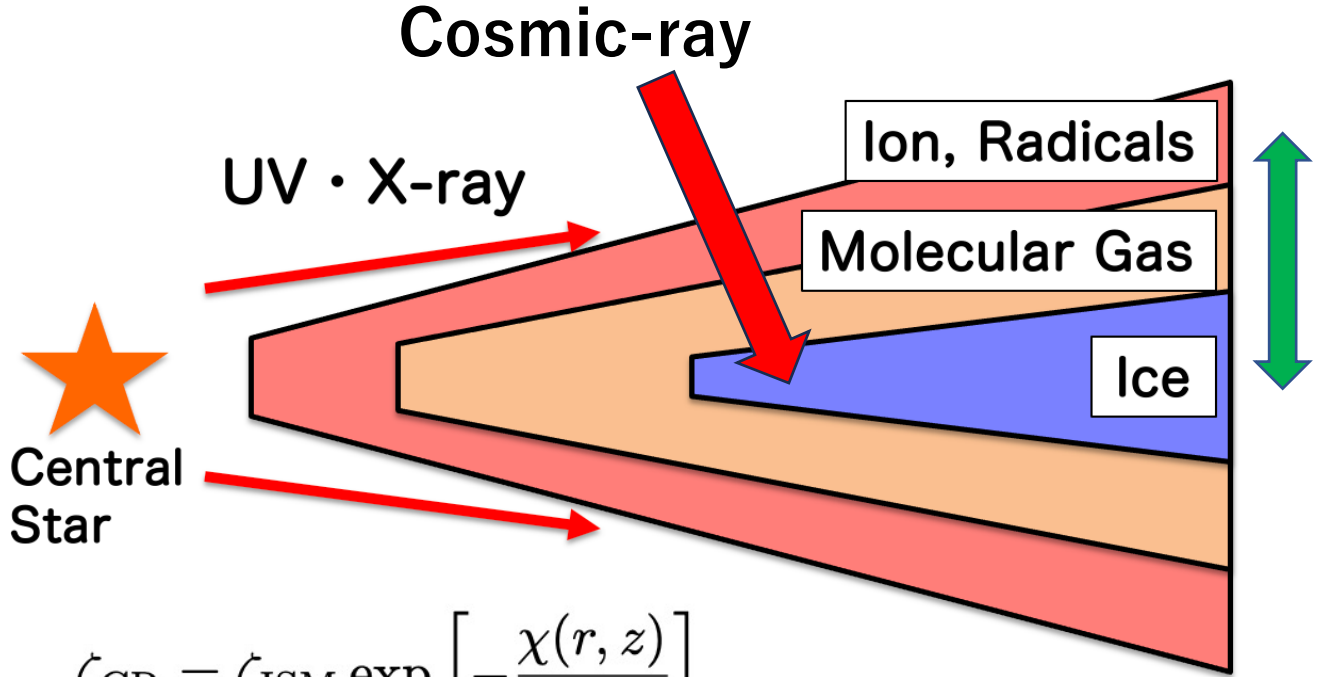
Studies of chemical structures in protoplanetary disks and protostellar objects (Modeling + Observations)

- Clarify the formation process of planetary systems and water and organic molecules
- Understanding the atmospheric structures of various exoplanets and the origin of the chemical composition of primitive comets and asteroids.

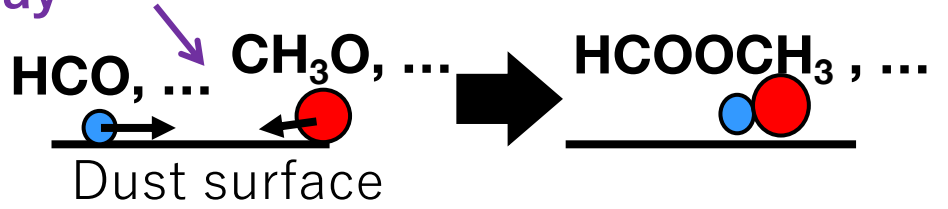
Cosmic-ray ionisation in protoplanetary disks

UV/X-ray/CR is important for chemistry in the vertical direction

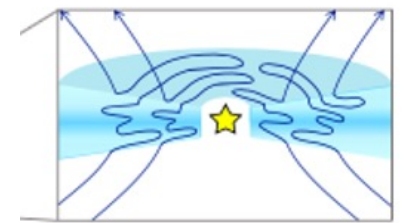
see e.g., Notsu et al. (2021, 2022, 2026)
 Rab et al. (2017)
 Fujii & Kimura (2022)
 Washinoue et al. (2024)



UV
Cosmic-ray
X-ray



Magneto rotational Instability (MRI)



$$\zeta_{CR} = \zeta_{ISM} \exp \left[-\frac{\chi(r, z)}{\chi_{CR}} \right]$$

Cosmic ray ionisation rate ζ_{CR}

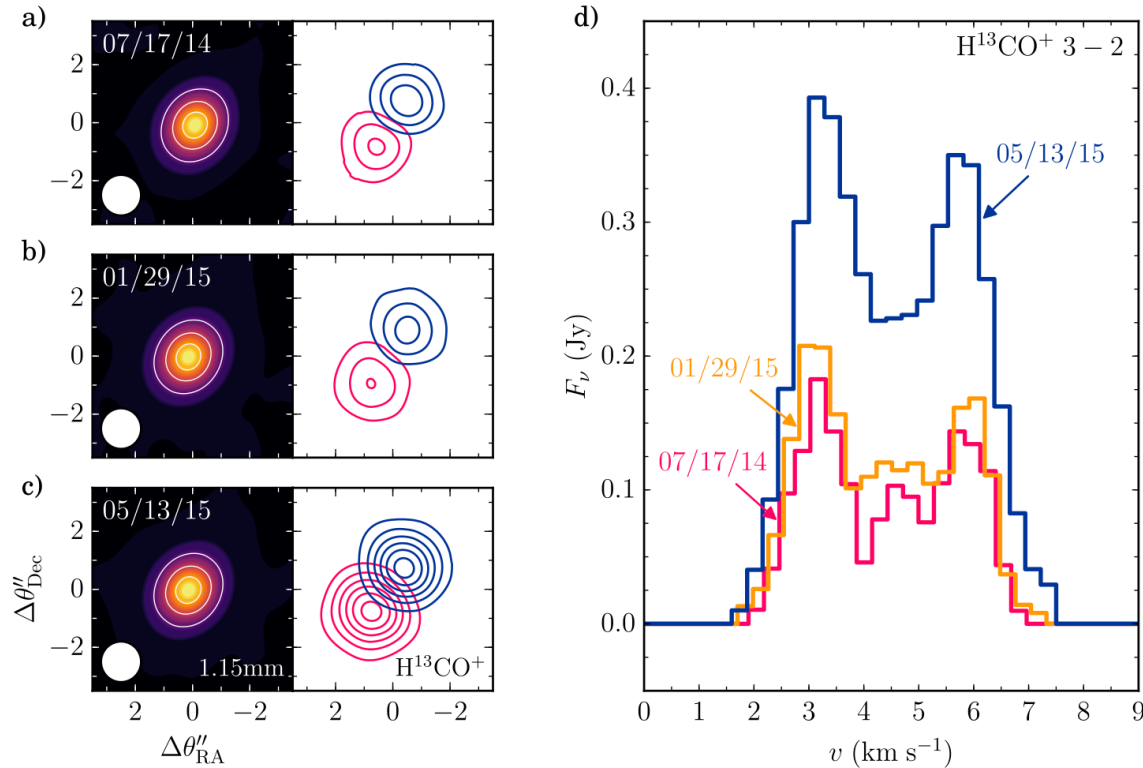
cf. Takasao-san's talk
 Namekata-san's talk

Main sources of disk ionization

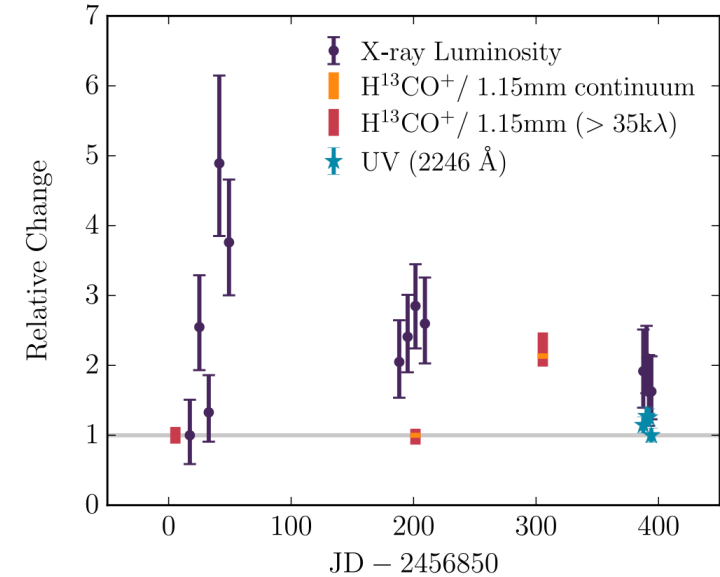
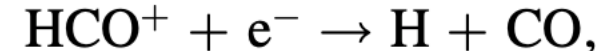
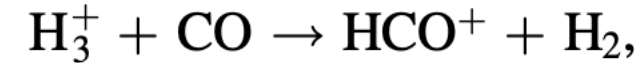
Galactic cosmic-ray ($\zeta_{CR} \sim 10^{-17} \text{ s}^{-1}$ in nearby clouds)
High energy particle from protostars
X-ray from protostars
 Radiative decay such as ^{26}Al ($< 10^{-19} - 10^{-18} \text{ s}^{-1}$)

X-ray induced time-domain chemistry in protoplanetary disks

Cleeves et al. (2017): X-ray induced chemistry (ALMA observations)



See also Waggoner & Cleeves (2022)



In Class II protoplanetary disk surfaces,
 H^{13}CO^+ are formed by strong X-ray flares in the disk surface

cf. Inoue...Enoto, Takasao, Notsu et al. (in prep.)

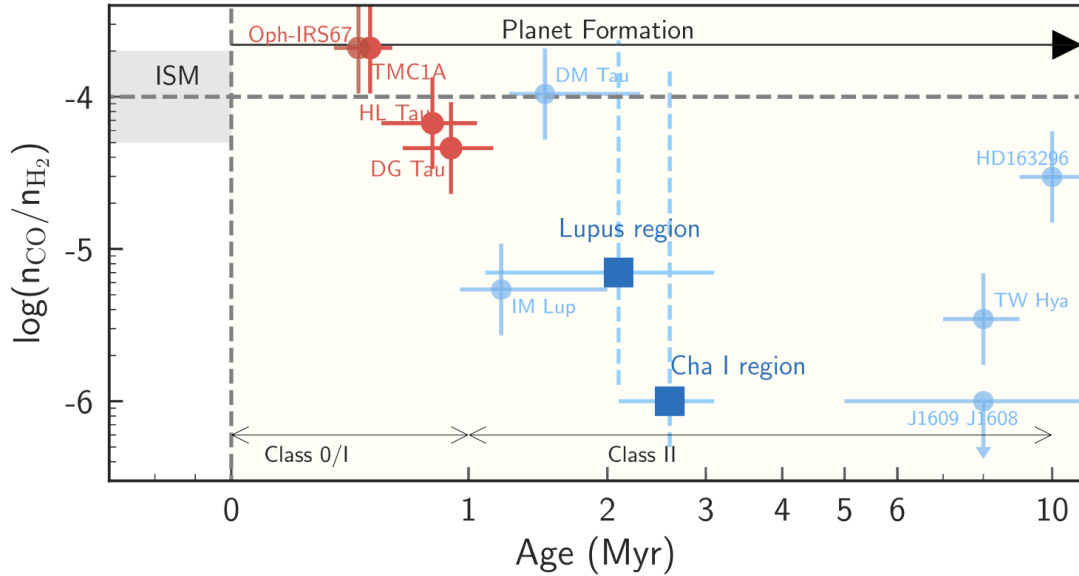
X-ray induced (time-domain) chemistry

→ **Potential synergies with X-ray (XRISM etc.) and mm/submm (ALMA etc.) observations**

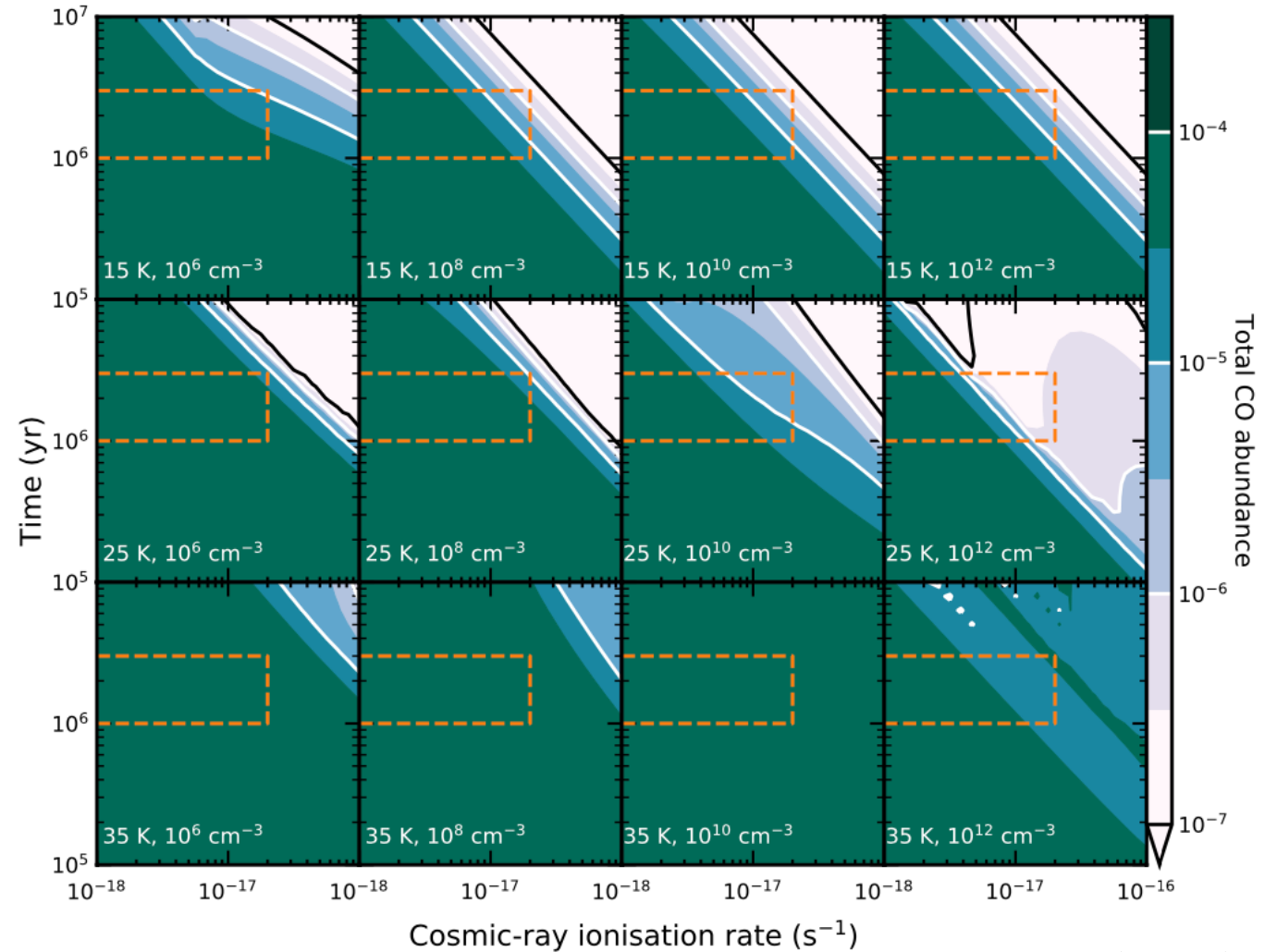
CO depletion & Cosmic-ray ionisation

Observations

Zhang et al. 2020



Effects of cosmic-ray ionization on CO chemical depletion



Bosman et al. (2018)

Bosman et al. (2018): no chemical processing of CO takes place on 1–3 Myr timescales for low cosmic-ray ionisation rates ($<5 \times 10^{-18} \text{ s}^{-1}$)

COSMIC-RAY IONISATION TRACERS

diffuse clouds

OH, HD, NH

Black & Dalgarno (1977)
Hartquist+ (1978)
van Dishoeck & Black (1986)
Federman+ (1996)

H₃⁺, OH⁺, H₂O⁺

Geballe+ (1999),
McCall+ (2003), Gerin+(2010)
Indriolo+ (2009,2012,2015,2026),
Obolentseva+(2024)

ArH⁺

Neufeld & Wolfire (2017)

CO, OH, CH, HCO⁺

Luo+ (2023a,b)

dense clouds

HCO⁺, DCO⁺

Guélin+ (1977), Caselli+ (1998)
Maret & Bergin (2007), Cabedo+ (2023)
Pineda+ (2024)

N₂H⁺, HCO⁺, N₂D⁺, DCO⁺

Redaelli+ (2021)

sulfur chemistry

Fuente+ (2016)

PO⁺

Rivilla+ (2022b)

H₂

Bialy (2020)
Padovani+ (2022)
Bialy, Belli, Padovani (2022)
Bialy+ (2026), Neufeld+(2026)

JWST

oH₂D⁺

Bovino+ (2020)
Sabatini+ (2023)
Redaelli+ (2024)
Socci+ (2024)

circumstellar discs

HCO⁺, N₂H⁺

oH₂D⁺

Ceccarelli+(2004)
Cleeves+ (2014)

protostellar jets (shocks)

HCO⁺, N₂H⁺

Podio+ (2014),
Ceccarelli+ (2014)
Rab+ (2017)

HC₃N, HC₅N

Fontani+ (2017)

c-C₃H₂

Favre+ (2018)

高棹さんスライドより
元資料: Padovani氏スライド
<https://spice-workshop.github.io>

ALMA observations: ionisation rates increase in the inner regions around protostars? (>500 au scales)

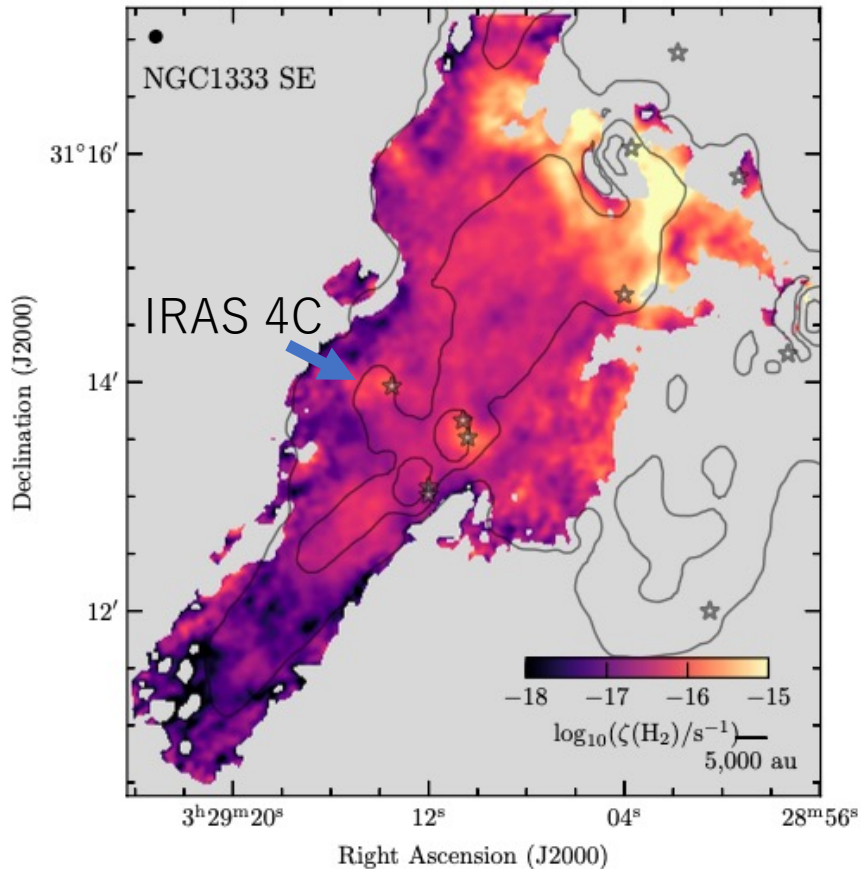
Pineda et al. (2024)

ISM average CR ionization rate: $\sim 10^{-17} \text{ s}^{-1}$

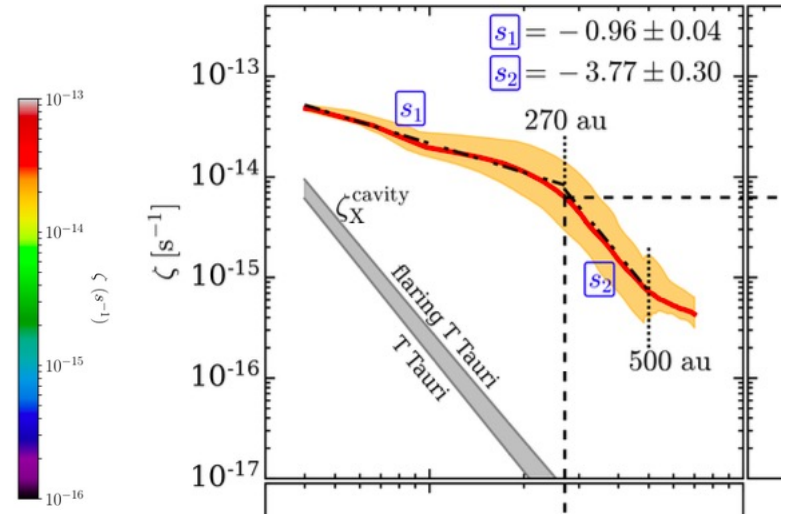
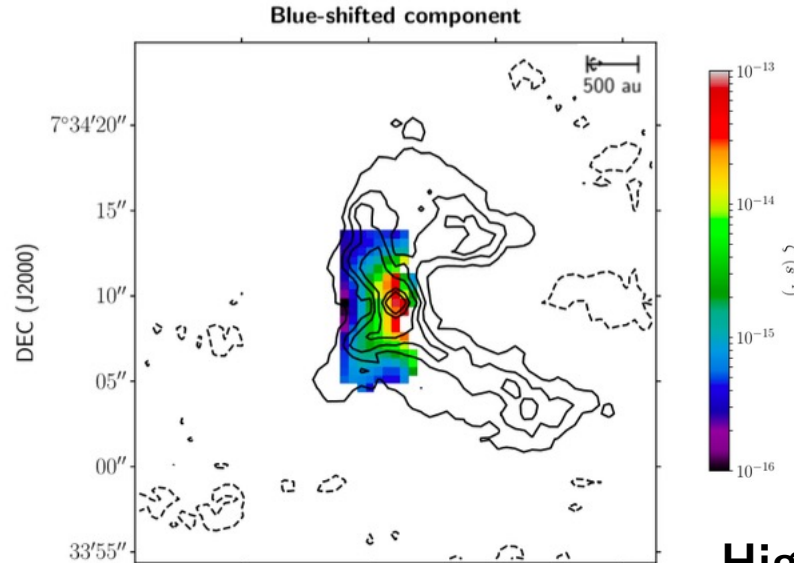
Cabedo et al. (2023)

Low-mass (\sim solar-mass) protostar forming regions

Envelope around Low-mass protostar B335



High ionization rates ($\zeta_{\text{CR}} > 10^{-16} \text{ s}^{-1}$) around protostars (>1000 au scale)



High ionization rates ($\sim 10^{-14} \text{ s}^{-1}$) around protostars (>100 au scale)

Cautions: These observations used CO, HCO⁺, DCO⁺ lines Redaelli et al. (2024): ortho-H₂D⁺ is needed for estimation with higher accuracy (\rightarrow ALMA/UNIC Large Program)

High energy particles accelerated by stellar flares and/or protostellar jets?

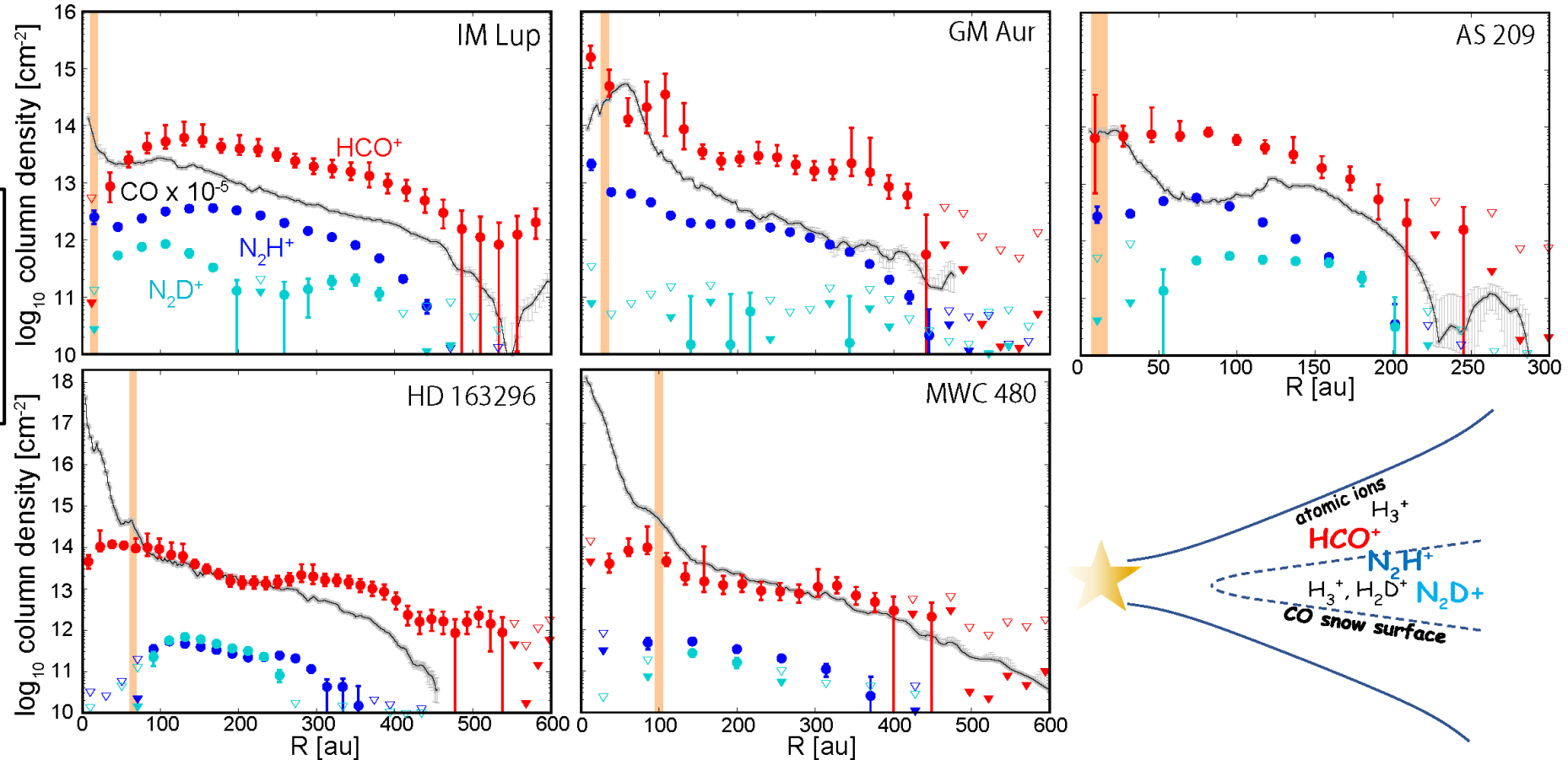
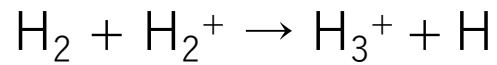
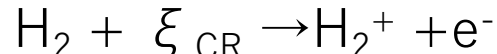
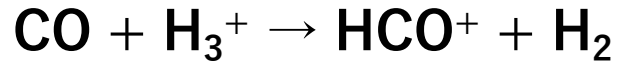
Class II disk studies: Radial variations in ionization degree



More Herbig disk chemistry including ionisation → ALMA LP CHEER (Notsu is co-I)

ALMA/MAPS

Aikawa et al. (2021)



See also

- e.g., Seifert et al. (2021),
- van't Hoff et al. (2022),
- Fujii & Kimura (2022)
- Long et al. (2024)

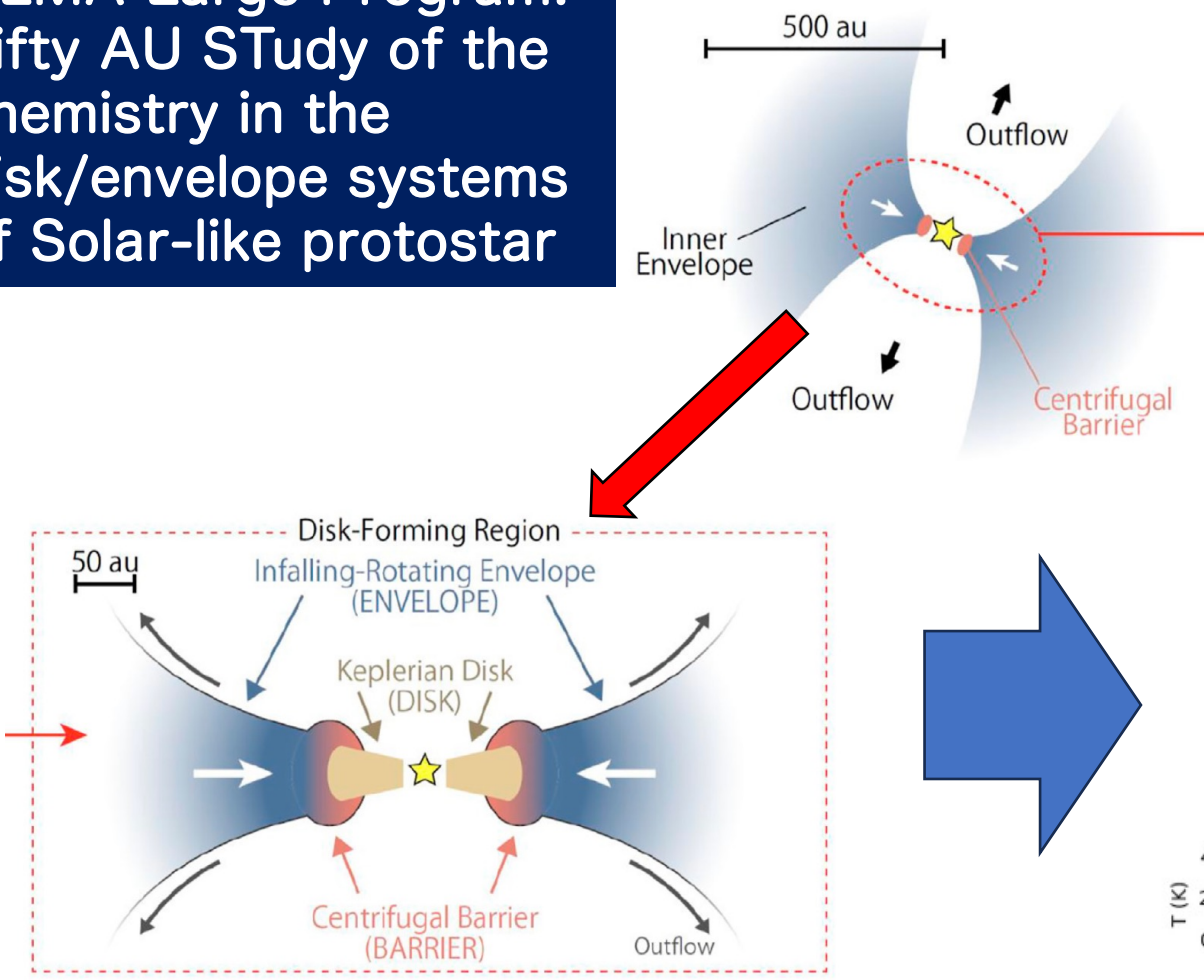
Recent Class II disk observation: the HCO⁺ abundances and the cosmic-ray ionization degree decrease in the inner higher density region

Our observation: Radial variations of ionization degree in the Class 0 disk IRAS 4C

ALMA Large Program: Fifty AU Study of the chemistry in the disk/envelope systems of Solar-like protostar

Codella et al. (2021)
PI: Satoshi Yamamoto

See FAUST papers (I- XXXII)



FAUST View of Solar-type Protostars

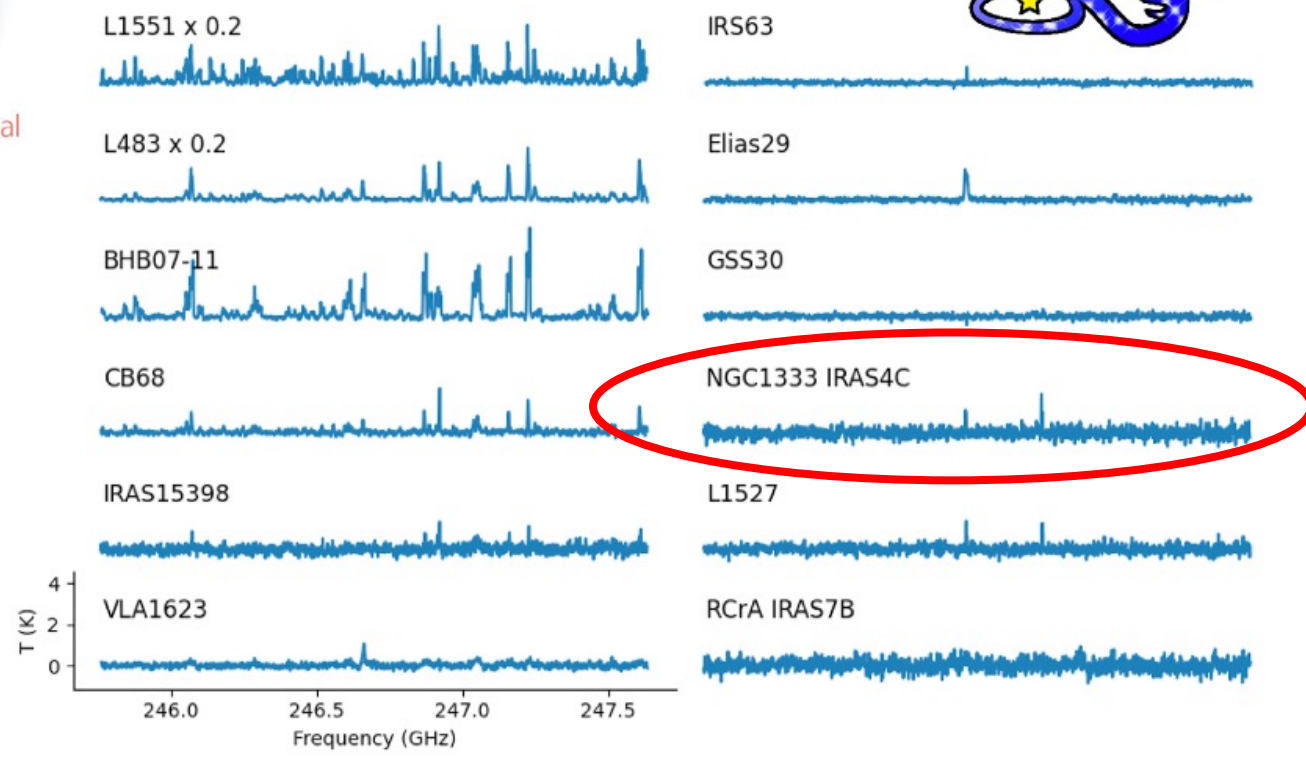


TABLE 1 | List of the frequency windows and of the species covered by the selected backends, divided in four groups (see Section 2.2).

Setup	Frequency (GHz)	Zones	Molecular complexity	Gas Ionization	Molecular deuteration
1	214.0–219.0 229.0–234.0	c-C ₃ H ₂ , CH ₃ OH, SO SiO, H ₂ CO, C ¹⁸ O	CH ₃ OH, NH ₂ CHO CH ₃ CHO, HCOOCH ₃	DCO ⁺	N ₂ D ⁺ , D ₂ CO
2	242.5–247.5 257.5–262.5	c-C ₃ H ₂ , CS CH ₃ OH, SO	CH ₃ OH, NH ₂ CHO CH ₃ CHO, HCOOCH ₃ CH ₃ OCH ₃	H ¹³ CO ⁺	HD ₂ O, CH ₂ DOH
3	85.0–89.0 97.0–101.0	CH ₃ OH, HC ₃ N	CH ₃ OH, ¹³ CH ₃ OH	N ₂ H ⁺	c-C ₃ HD



IRAS 4C: Notsu et al. (2026, submitted)

論文投稿中のため、
IRAS4C関連スライドをcutしています

1. Overview: Cosmic-ray ionisation in protoplanetary disks and protostellar envelopes

- Effects of ionization on chemical (and physical) evolution
- Cosmic-ray ionization rates in protoplanetary disks and protostellar envelopes
- X-ray ionization and chemistry

2. FAUST: Chemical layered structures in the disk around a low-mass Class 0 protostar NGC 1333 IRAS 4C

- Vertical Layered structures in the disk:
 - $C^{18}O/H_2CO$ (High density region) \rightarrow $CCH/c-C_3H_2$ (Surface)
- Radial variations of $H^{13}CO^+/CO$ ratio
 - \rightarrow Cosmic-ray ionization degree and rates are larger in the outer disk region
- Even Class 0 disk has vertical/radial chemical variation structures!

Future: More ionization observations for disks, and discussion with disk chemical evolution!