Science Strategy of NAOJ
: Star and Planet Formation

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On behalf of Science Roadmap Committee of NAOJ

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Star & Planet Formation: Introduction
星惑星形成分野の概観

- The question of **how planetary systems form, evolve physically and chemically, and ultimately give rise to life such as ours** is *one of the fundamental challenges of humanity*.
  - Recent **high-angular-resolution observations** with large ground-based optical/infrared telescopes, ALMA, and JWST have enabled detailed studies of planetary-system-scale objects, including **protostellar disks**, **protoplanetary disks**, and **debris disks**. These observations have revealed signatures of **planet formation**, **the microphysical dust processes** that constitute its first steps, and the pathways of **material evolution into planetary systems**.
  - At the same time, observations of star-forming regions in **a wide range of environments**, including the Galactic center, the outer Galaxy, and nearby galaxies such as the Magellanic Clouds, have become possible, shedding new light on **their physical and chemical evolution under diverse conditions**.
- Through these observations, we expect to uncover **the formation processes of diverse star-planet systems**, **the evolution of molecules that may serve as ingredients for life**, and **the material evolution that ultimately leads to the atmospheres of exoplanets**.

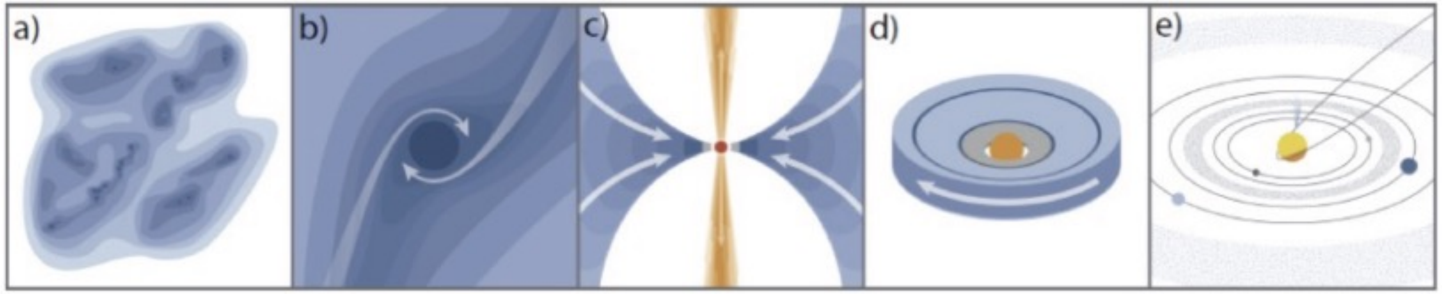
Goals in Star & Planet Formation
星惑星形成分野の目標

銀河系形成時から現在に至る多様な環境の中で、星惑星系がどのように形成され、多様な星や惑星系へと進化したのか、そこでどのように物質が進化し、生命起源物質が生成されたのかを探る。

- Ultimate Goal of Star and Planet Formation Study (当該分野の究極的な目的)
  - We aim to investigate **how star-planet systems formed and evolved into the diverse populations of stars and planetary systems observed today**, **across the wide range of environments** that have existed from the epoch of Galaxy formation to the present day.
  - We further seek to uncover **how matter evolved within these systems** and **how the chemical ingredients for the origin of life were produced**.
- Goals in Star and Planet Formation (当該分野の目標)
  - **Understanding the Formation Processes of Stars and Planetary Systems 星・惑星系の形成過程の解明**
    - We investigate how stars and planetary systems form in molecular clouds under diverse galactic environments -- shaped by turbulence, magnetic fields, metallicity, and high-energy radiation -- and how these conditions drive the variety observed in stellar and planetary systems.
  - **Understanding the Evolution of Matter Toward Planetary Systems 惑星系に至る物質進化の解明**
    - We explore how matter evolves from diffuse atomic gas to molecular clouds, protoplanetary disks, and finally to star-planet systems, and how different environments shape the chemical complexity that ultimately leads to life-bearing ingredients.

Current Status of Star & Planet Formation Study 現在までの到達点

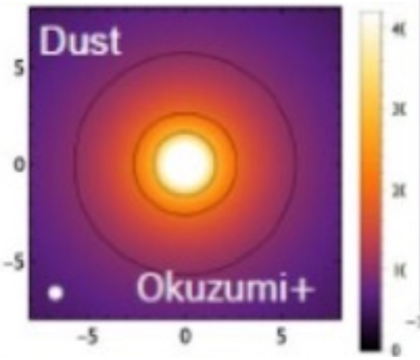
- Understanding the Formation Processes of Stars and Planetary Systems
  - Gas and Dust Distributions in Protostellar, Protoplanetary, and Debris Disks, and Planet Formation
  - Protostellar Objects and Star Formation
  - Interstellar Matter on Galactic Scales and the Star-Formation Cycle
- Understanding the Evolution of Matter Toward Planetary Systems
  - Gas and Dust Distributions in Protostellar, Protoplanetary, and Debris Disks, and Planet Formation
  - Protostellar Objects and Star Formation

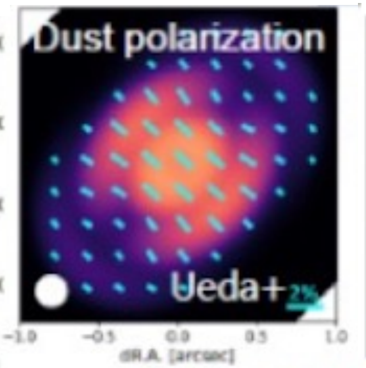


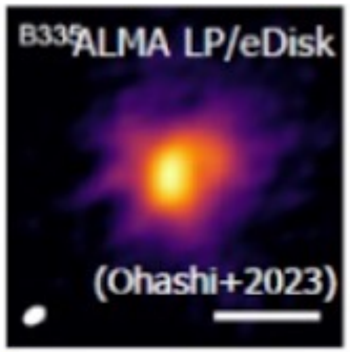
Oberg & Bergin 2021, Physics Reports, 893, 1

Current Status of Star & Planet Formation Study

- Gas and Dust Distributions in Protostellar, Protoplanetary, and Debris Disks, and Planet Formation using large optical/infrared telescopes (Subaru, VLT, Keck, etc.) and ALMA
  - Detection of **structures such as ring, gap, spirals** (Fukagawa et al. 2004; Andrews et al. 2016; Tsukagoshi et al. 2022), **featureless young disk** (Ohashi et al. 2023), and **signatures of planet formation** through deviations from Keplerian rotation (Pinte et al. 2025). ➔ **advancement of theoretical models** for such structures (e.g., Dong et al. 2015; Kanagawa et al. 2015; Okuzumi et al. 2016)
  - **Gas observations of debris disks** using ALMA have shed light on **disk gas dispersal timescales**, which are closely linked to the planet formation (Dent et al. 2014; Higuchi et al. 2019).
  - **Dust microphysics in disks**, such as **radial drift** indicated by differing radial distributions of dust and gas, **dust settling toward the midplane**, **self-scattering polarization** constraining **dust-size distributions** and **porosity** (Andrews 2020; Tazaki et al. 2025; Tsukagoshi et al. 2016; Kataoka et al. 2016)

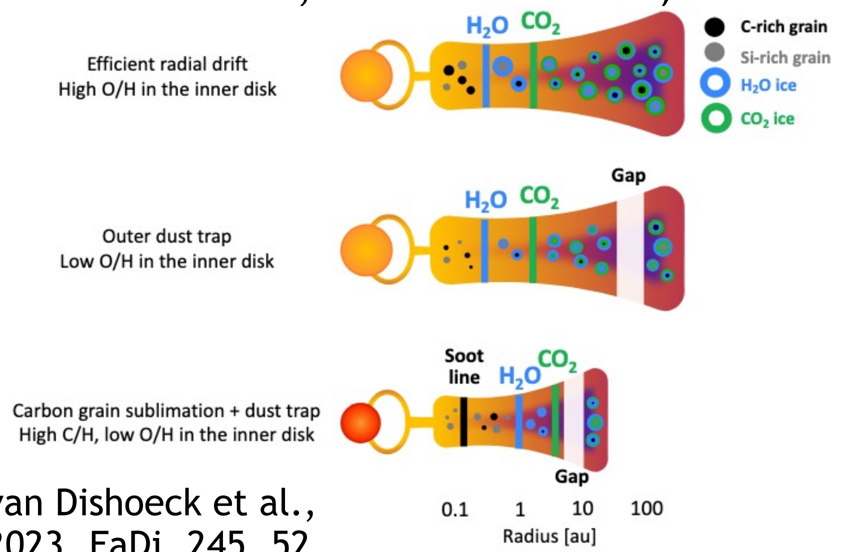




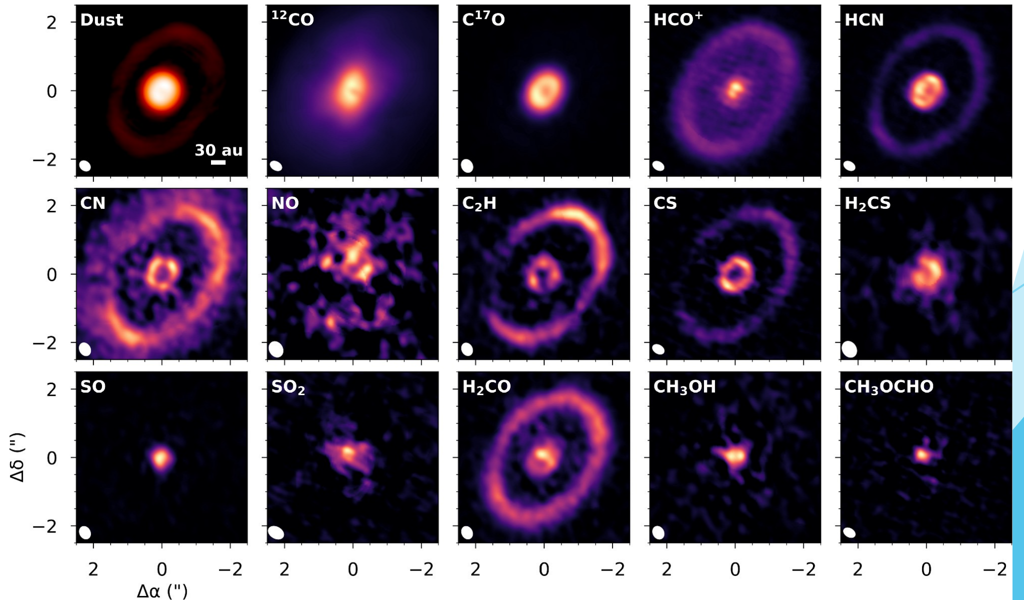


Current Status of Star & Planet Formation Study

- Understanding the Evolution of Matter Toward Planetary Systems
  - Different molecules exhibit ring and gap structures that do not necessarily coincide with dust substructures, suggesting **chemical and physical segregation in planet-forming disks** (Law et al. 2021).
  - **Complex organic molecules** have been detected in disks with ALMA, and **aromatic molecules** and molecular **ions** have been identified with JWST (Walsh et al. 2016; van Dishoeck et al. 2023).
  - Observations with large ground-based IR telescopes and JWST have detected **water in gas and ice** across multiple disks (Honda et al. 2009; Banzatti et al. 2023; Sturm et al. 2023).
  - ALMA has revealed the distributions of **rare isotopologues of H, N, and C** (Cataldi et al. 2021; Hily-Blant et al. 2019; Yoshida et al. 2022)
  - JWST has detected **isotopologues of carbon-bearing molecules** in both **the gas and ice phases** (van Dishoeck et al. 2023; Sturm et al. 2023).



van Dishoeck et al., 2023, FaDi, 245, 52

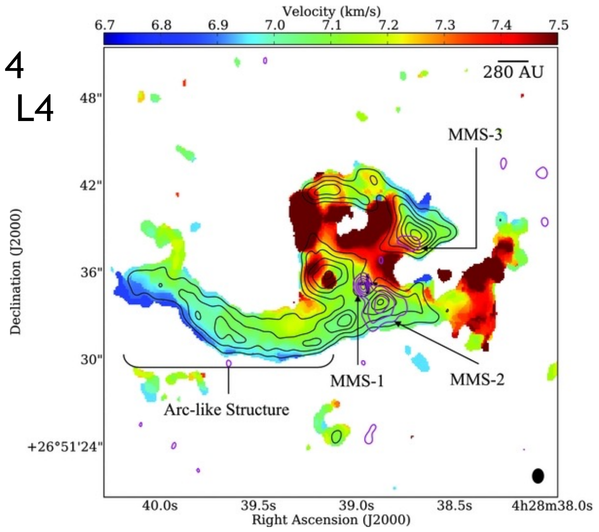


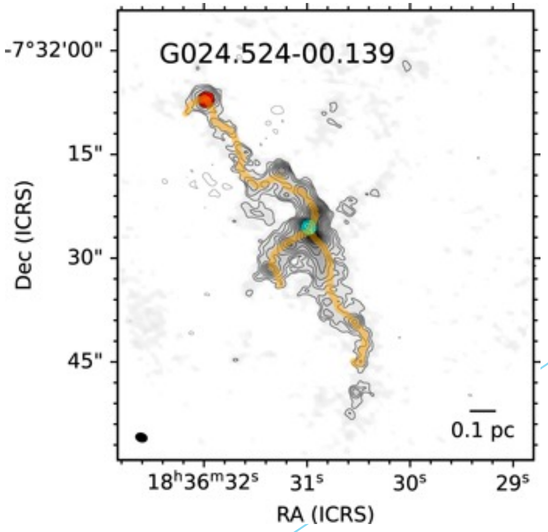
Booth, Nomura, Notsu, et al. 2024, AJ, 167, 164

Current Status of Star & Planet Formation Study

- Protostars and Star Formation: Recent Advances with ALMA and JWST
  - Resolving structures on **scales comparable to numerical simulations**, placing strong constraints on the physical and chemical structures of protostellar systems
  - High-resolution imaging of protostellar outflows supports **magneto-centrifugal winds** as the driving mechanism (Alves et al. 2017; Oya et al. 2018).
  - **Binary formation** driven by gravitational instability and turbulence (Tobin et al. 2016; Tokuda et al. 2014)
  - Discovery of **accretion streamers** indicates **intermittent mass infall onto protostars** (Pineda et al. 2020)
  - high-mass star formation in filament–hub systems, filament formation triggered by molecular-cloud collisions, and mass accretion onto star-forming cores ➔ all representing **a non-isolated mode of star formation**, which is ***distinct from "classical isolated-core scenarios***"; now being interpreted through comparisons with **numerical simulations** (Hacar et al. 2018; Tokuda et al. 2019; Morii et al. 2023)

Tokuda et al. 2014
ApJ Letters, 789, L4

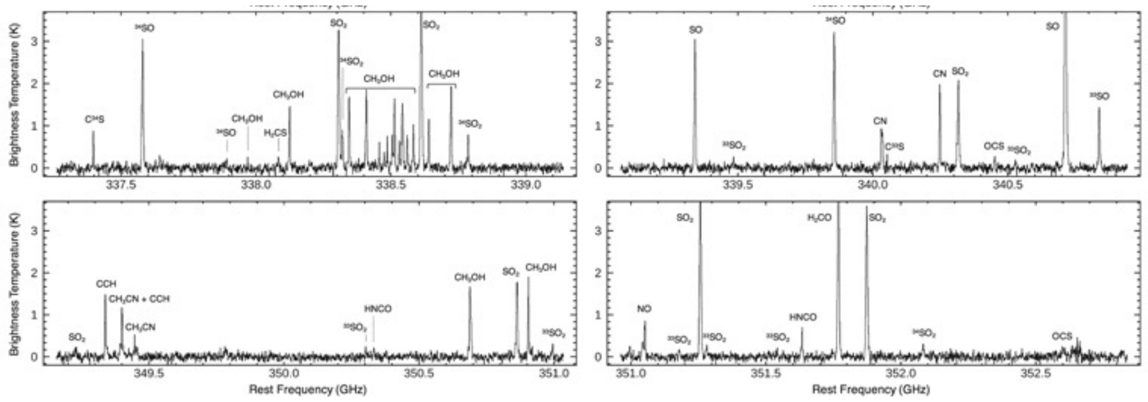




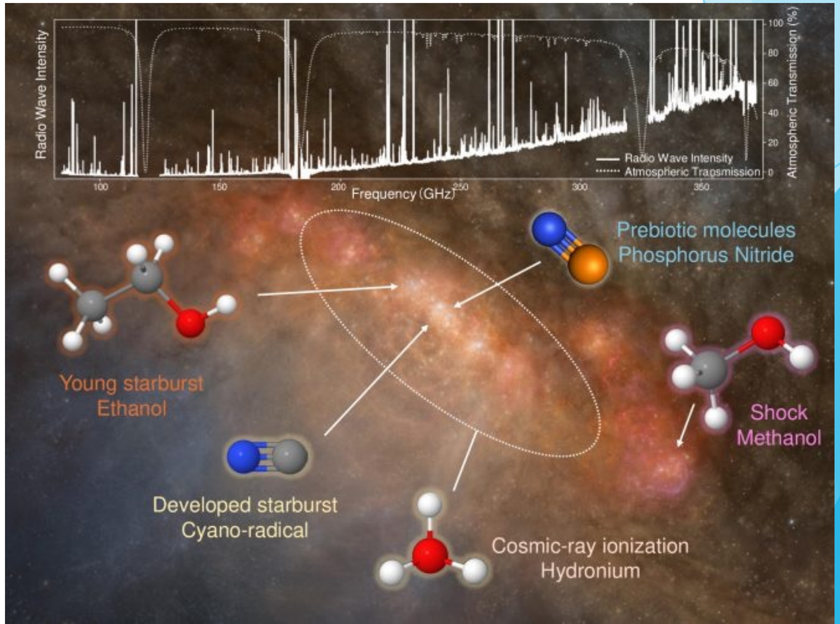
Morii et al. 2023
ApJ, 950, 148

Current Status of Star & Planet Formation Study

- Protostars and Star Formation: Chemical and Physical Diagnostics
  - In low-mass cores, narrow line widths and minimal blending enable the detection of many new species, including **precursors of biomolecules** and **rare isotopologues** (Jørgensen et al. 2020).
  - JWST observations have opened a new window on **interstellar ices**, revealing **complex organic molecules** and **rare carbon isotopologues** previously inaccessible (Rocha et al. 2024; Brünken et al. 2024).
  - ALMA and JWST observations of star-forming regions in the outer Galaxy and Magellanic Clouds show markedly different chemical evolution; Some cores exhibit extremely low methanol abundances, highlighting the **impact of low metallicity on molecular formation pathways** (Shimonishi et al. 2020).
  - Progress in molecular-line observations of nearby starburst galaxies and AGN-host galaxies reveals environments shaped by **strong UV/X-ray fields** and **enhanced turbulence**; similarities to conditions in the Galactic Center (Martín et al. 2015; Harada et al. 2024)



Shimonishi et al. 2020, ApJ, 891, 164



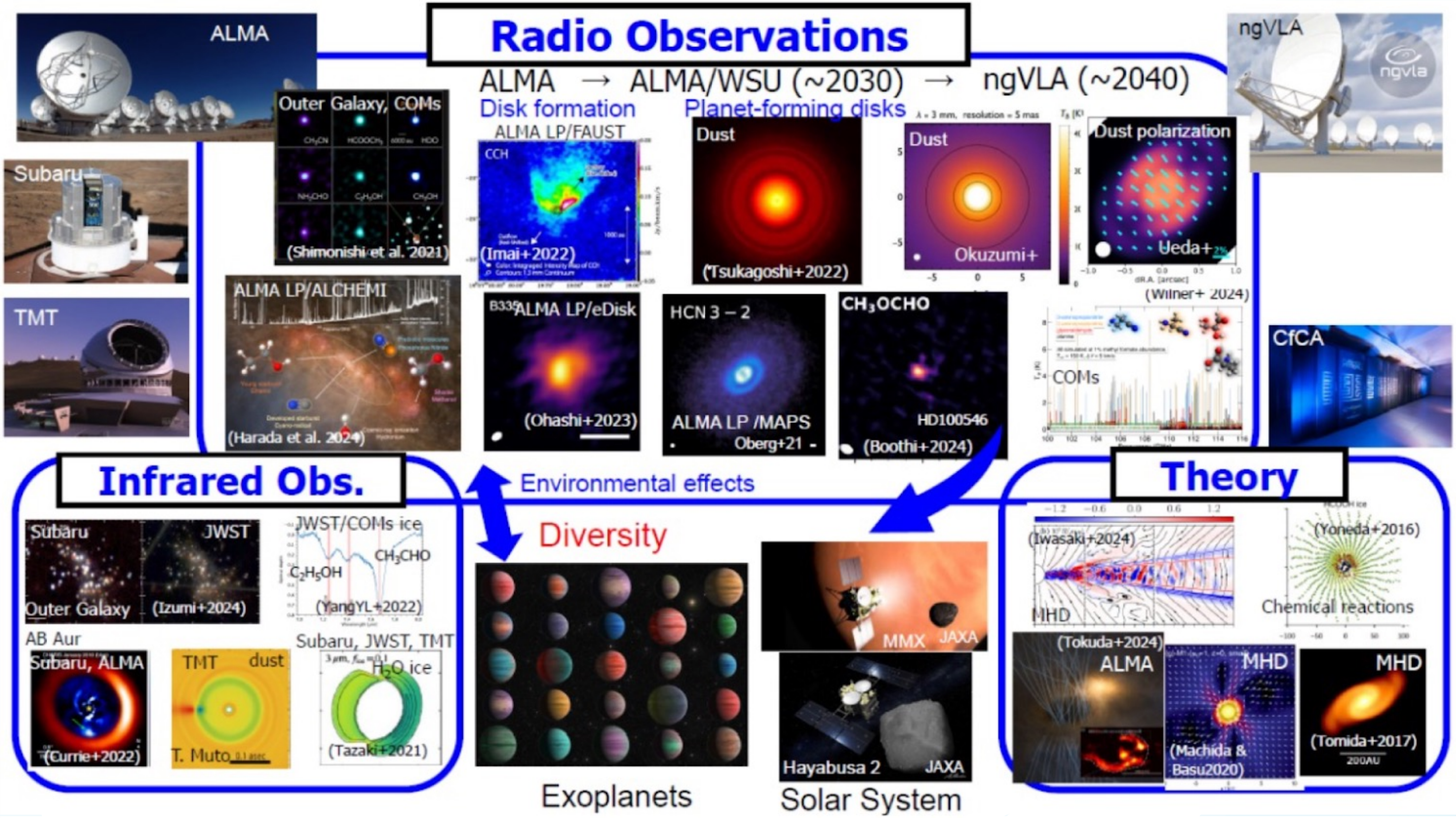
Harada et al. 2024, ApJS, 271, 38

Future Trends 今後の世界的動向

small scales ↕ large scales

- **Understanding the Formation Processes of Stars and Planetary Systems**
  - Detection of Newly Formed Planets Embedded in Protoplanetary Disks: JWST, Roman, ELTs with coronagraph, ALMA2/WSU, ngVLA
  - Gas and Dust Distributions in Protostellar, Protoplanetary, and Debris Disks, and Planet Formation: ALMA2, ELT; The ngVLA will enable observations of the **innermost disk regions near the midplane**, which are difficult with ALMA (Ricci et al. 2023); FIR polarization using PRIMA (Tazaki et al. 2023); GREX-PLUS
  - Protostellar Objects and Star Formation: ALMA2, ELT, ngVLA
  - Environmental Effects Leading to Diversity in Stars and Planetary Systems: large optical/IR telescopes, ALMA2, ELT, SKA, ngVLA, LST/AtLAST
  - Environmental Dependence of Molecular Cloud Properties and Star Formation within Galaxies; Gas Inflow Toward the Galactic Center and (active) galactic nuclei; Galactic Outflows and the Circulation of Matter ("Baryonic cycle"): ALMA2; SKA, ngVLA
- **Understanding the Evolution of Matter Toward Planetary Systems**
  - Gas and Dust Distributions in Protostellar, Protoplanetary, and Debris Disks, and Planet Formation: ALMA2, JWST, ELT, ngVLA; snowline using PRIMA, GREX-PLUS
  - Search for Complex Organic Molecules and Refractory Species -- Ingredients for Life: Yebes, IRAM, GBT (McGuire 2022; Jimenez-Serra et al. 2022), ALMA2, ELT, ngVLA, SKA, LST/AtLAST, combined with numerical simulations → the **diversity of exoplanetary systems** and the **origins of life**
  - Observations of the Multi-phase Interstellar Medium in Galaxies: HI with SKA, ngVLA; molecules with ALMA2; fine structure lines with PRIMA

Science Strategy of NAOJ 国立天文台の科学戦略



Science Strategy of NAOJ 国立天文台の科学戦略

■Understanding the Formation Processes and Diversity of Stars and Planetary Systems (1/3)

- Formation processes span an enormous dynamic range
  - From sub-AU scales around protostars to molecular-cloud scales (~8 orders of magnitude)
  - Similar large dynamic ranges for angular momentum, magnetic fields (≥8 orders), and gas density (up to 20 orders)
- Environmental effects across galactic scales
  - Star/planet formation likely varies across kpc–galaxy scales (spiral arm/inter-arm, galaxy morphology, AGN activity)
  - Key unexplored factors: metallicity, intense radiation fields (starbursts/AGN), cosmic-ray environments
  - Diversity and origins of the IMF, binary fraction, and cluster formation conditions
- Required approach in the next mid-term plan
  - Advance high-resolution studies for disks and protostars
  - Conduct wide-area observations from molecular cloud cores/filaments to galaxy-scale ISM
  - Promote integrated observational + theoretical programs for unified understanding

Science Strategy of NAOJ 国立天文台の科学戦略

■Understanding the Formation Processes and Diversity of Stars and Planetary Systems (2/3)

- High-resolution disk studies with **ALMA/ALMA2**
  - Direct imaging of rings, gaps, snowlines in protoplanetary disks; Capture structural signatures of planet formation and its diversity
  - High-dispersion IR spectroscopy using **GREX-PLUS** to detect ice snowlines
- Detecting fine disk structures caused by Earth-mass planets
  - Requires higher sensitivity and resolution than current **ALMA**; **SKA** high-frequency bands and **ngVLA** will constrain initial conditions that set exoplanet diversity
- Gas inflow from galactic to molecular-cloud scales
  - HI 21 cm observations with **SKA** and **ngVLA** to trace gas supply mechanisms; Essential for understanding environmental dependence of star formation–Star/planet formation likely varies across kpc–galaxy scales (spiral arm/inter-arm, galaxy morphology, AGN activity)
  - Key unexplored factors: metallicity, intense radiation fields (starbursts/AGN), cosmic-ray environments → Diversity and origins of the IMF, binary fraction, and cluster formation conditions
- Monitoring episodic accretion in massive star formation
  - VLBI observations of masers to capture burst-driven inflow events using **University VLBI networks** and **East-Asian VLBI**

Science Strategy of NAOJ 国立天文台の科学戦略

■Understanding the Formation Processes and Diversity of Stars and Planetary Systems (3/3)

- Wide-field millimeter/submillimeter spectral imaging
  - Statistical characterization of star formation across environments; need for wide [CI] surveys and **large-area polarization mapping** to reveal **magnetic-field roles**,
  - from molecular cloud cores/filaments to galaxy-scale ISM
  - Key facilities: **NRO 45m**, **ASTE 10m**, **LST/AtLAST**, **ATT** for THz [CI] ($^3P_2$-$^3P_1$)
- Wide-field optical/IR surveys and spectroscopy of protostars and young clusters
  - Key facilities: **Subaru-2** / **Subaru-3**
  - essential for quantifying diversity in formation environments
- Theory–observation integration
  - Numerical simulations to reproduce observed phenomena and extract universal laws
  - Coordination with **CfCA** and **joint observational-theoretical frameworks**

Understanding the Formation Processes and Diversity of Stars and Planetary Systems
星・惑星系の形成過程とその多様性の解明

work in progress
please provide feedback

Theme	Methods (wavelengths, characteristics)	Projects in the 5th Mid-term Plan	Expected Operation
Diversity in Disk Structures of Protostellar / Protoplanetary Systems	High-resolution imaging from cm to submillimeter wavelengths	**(In operation)** ALMA2 **(Development)** SKA-high, ngVLA	**SKA** (2031) **ngVLA** (2041)
	Detection of snowlines via near-IR and high-dispersion spectroscopy	**(In operation)** GREX-PLUS	**GREX-PLUS**
Diversity in Dynamical Processes of Massive Star Formation	High-resolution imaging of masers and radio continuum (cm-mm)	**(In operation)** JVN	—
Environmental Effects on Star Formation	21 cm line, millimeter/submillimeter spectroscopy; wide-field spectral imaging	**(In operation)** NRO, ASTE **(Construction)** SKA-Mid **(Studies)** ngVLA, LST/AtLAST, ATT30m	**ngVLA** (2041) **LST/AtLAST** (2040s) **ATT30m** (mid-2040s)
Low-mass Protostars and Young Stellar Objects	Observations (near-infrared, wide-field imaging)	**(Current)** Subaru-2 **(Development)** Subaru-3	**Subaru-3** (2032)
Understanding Diversity in Star and Planet Formation with Physical Models	Theory	**(Current)** CfCA	—

Science Strategy of NAOJ 国立天文台の科学戦略

■ Understanding the Evolution of Matter Toward Planetary Systems (1/2)

- Chemical and Material Evolution from Molecular Clouds to Planetary Systems
  - **Trace chemical evolution** from molecular clouds → protostars → disks → planets
  - Statistical understanding of **chemical diversity** is essential for explaining planetary compositions and habitability.
  - Remarkable **physical diversity** in disk structures (rings, spirals, asymmetries, etc.).
- Chemical Environment of Planet Formation
  - High-resolution ALMA observations map distributions of organics, water, and volatiles.
  - **Snowline locations** + **volatile distributions** constrain solid–gas separation and planetary compositions.
  - Snowlines may migrate due to variable accretion rates; maser monitoring (**VLBI**) can trace episodic inflows linked to chemical structure.
  - Push toward higher-sensitivity observations of larger molecules (mm–cm wavelengths).
  - Key facilities: **ALMA/ALMA2, SKA, ngVLA, GREX-PLUS** (mid-IR high-dispersion spectroscopy).
- Direct Characterization of Planet-forming Environments
  - High-sensitivity optical/NIR spectroscopy can detect Earth-mass planets and their forming environments.
  - Time-variable chemistry and fine compositional structures → on initial conditions of planet formation
  - Key facilities: **Subaru-2** / **Subaru-3, TMT**

Science Strategy of NAOJ 国立天文台の科学戦略

■Understanding the Evolution of Matter Toward Planetary Systems (2/2)

- Wide-area Molecular Surveys and Environmental Dependence
  - Wide-field mm/submm spectral imaging enables statistical comparisons across many star/planet-forming regions.
  - Reveal how chemical diversity depends on environment (stellar mass, radiation field, density, etc.).
  - Late-type stars and supernovae should also be surveyed to understand global matter circulation.
  - Provides basis for selecting representative ALMA follow-up targets.
  - Facilities: **NRO 45m**, **ASTE 10m** → future **LST/AtLAST**, **ATT**
- Systematic Comparison Across Evolutionary Stages
  - Follow chemical evolution consistently across stages: cloud cores → protostars → disks → planetary systems
  - Unified analysis combining high-resolution and wide-field data clarifies when specific chemical signatures emerge.
  - Important for placing the Solar System in a universal context
- Linking Molecular Evolution to Habitability
  - Key focus: origin and delivery of water and organic molecules to planets
  - Understanding these pathways constrains conditions for habitable environments.
  - Requires close integration of disk observations with physical-chemical modeling.
  - Theory and simulations (e.g., **CfCA**): essential for connecting formation pathways and diversity.

Understanding the Evolution of Matter Toward Planetary Systems
惑星系に至る物質進化とその多様性の解明

National Astronomical Observatory of Japan

work in progress
please provide feedback

Theme	Methods (wavelengths, characteristics)	Projects in the 5th Mid-term Plan	Expected Operation
From star-forming regions to chemical evolution in protostellar and protoplanetary disks	High-resolution imaging of individual objects from the centimeter to submillimeter regime	**(In operation)** ALMA2 **(Under development)** SKA-high, ngVLA	**SKA** (2031) **ngVLA** (2041)
	Wide-field millimeter/submillimeter spectral imaging surveys	**(In operation)** NRO, ASTE **(Proposed)** LST/AtLAST, ATT30m	**LST/AtLAST** (2040s) **ATT30m** (mid-2040s)
Characterizing the primordial atmospheres of Earth-sized planets	Near-infrared and high-dispersion spectroscopy	**(Current)** Subaru-2, TMT	**Subaru-3** (2032) **TMT** (2035)
Relationship between chemical evolution and habitable environments in planetary systems	Theory	**(Current)** CfCA	—

Summary まとめ

Any feedback would be sincerely appreciated

- Goals in Star and Planet Formation 当該分野の目標
  - Understanding the Formation Processes of Stars and Planetary Systems
  - Understanding the Evolution of Matter Toward Planetary Systems
- Science Strategy of NAOJ 国立天文台の科学戦略
  - Higher resolution studies of e.g., disks using ALMA2 → ALMA3, Subaru2/3 → TMT; GREX-PLUS (higher spectral resolution)

(Scopes of Subaru3 and ALMA3 are under discussion w/ communities)

  - Longer wavelengths: JVN → SKA, ngVLA
  - Wider surveys: Subaru2, NRO 45m, ASTE → Subaru3, LST/AtLAST, ATT
  - Theoretical studies/simulations: CfCA
  - (under discussion): FIR interferometer? PRIMA?

Observations x Theory framework?