RADIO ASTRONOMY RESEARCHES WITH THE NOBEYAMA 45 M TELESCOPE AND THE STATE-OF-THE-ART RECEIVERS

Mt. Yatsugatake & 45 m telescope

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Japanese 提案書 was distributed in 宇電懇, and comments are incorporated

ABSTRACT

- We promote radio astronomy researches using the Nobeyama 45 m telescope and state-of-the-art receivers, eQ for 30-50 GHz and 7BEE for 72-116 GHz.
- These instruments will be opened domestically and internationally within the framework of charged telescope time.

1. SUMMARY OF THE PROPOSAL(1)

- Science goals and objectives
  - We open up new scientific perspectives through wide-field imaging capabilities and general-purpose telescope operations. We provide opportunities for both scientific observation and technical development within the framework of charged telescope time.

1. SUMMARY OF THE PROPOSAL(2)

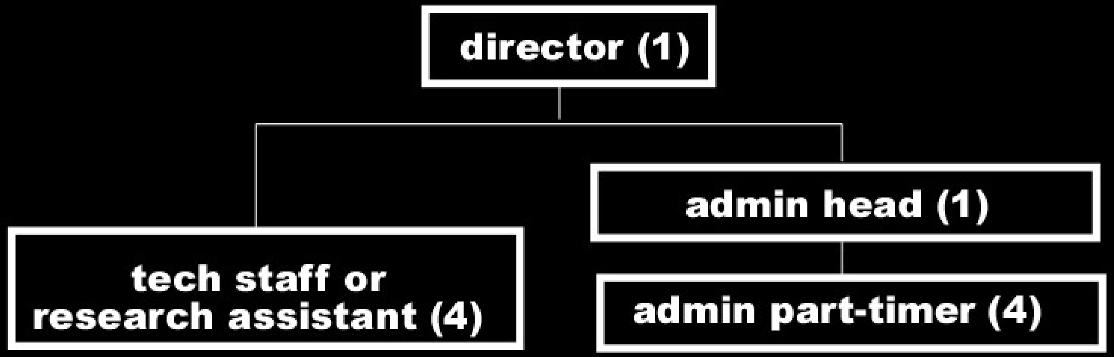
- Science investigations, instrumentation and data
  - hierarchical structure of molecular clouds, their evolution
  - star formation rate
  - researches in star formation based on observations of deuterated molecules
  - role of magnetic fields by observing the Zeeman effect
  - galaxy evolution based on CO emission line observations of redshifted galaxies
  - VLBI
  - time-domain astronomy.
- Equipments: 45m telescope, the new receivers eQ and 7BEE, the old receiver FOREST, and new spectrometers using FPGA. The new VLBI backend for both VLBI and Zeeman.

1. SUMMARY OF THE PROPOSAL(3)

- Operation
  - The charged telescope time that started in 2022 will continue (10,000 yen + tax per hour for PIs affiliated with domestic institutions, 30,000 yen + tax per hour for others).
- Key technologies
  - InP-based HEMT amplifiers for eQ and 7BEE (under commissioning).
  - New spectrometers using FPGA (to be built)
- Risks (single points of failure)
  - Risk of the SAM45 failure will be covered by the development of new spectrometers.
  - Risk of failure of the master collimator, we are in contact with the JAXA Institute of Space and Astronautical Science, which owns the same type of collimeter, just in case.

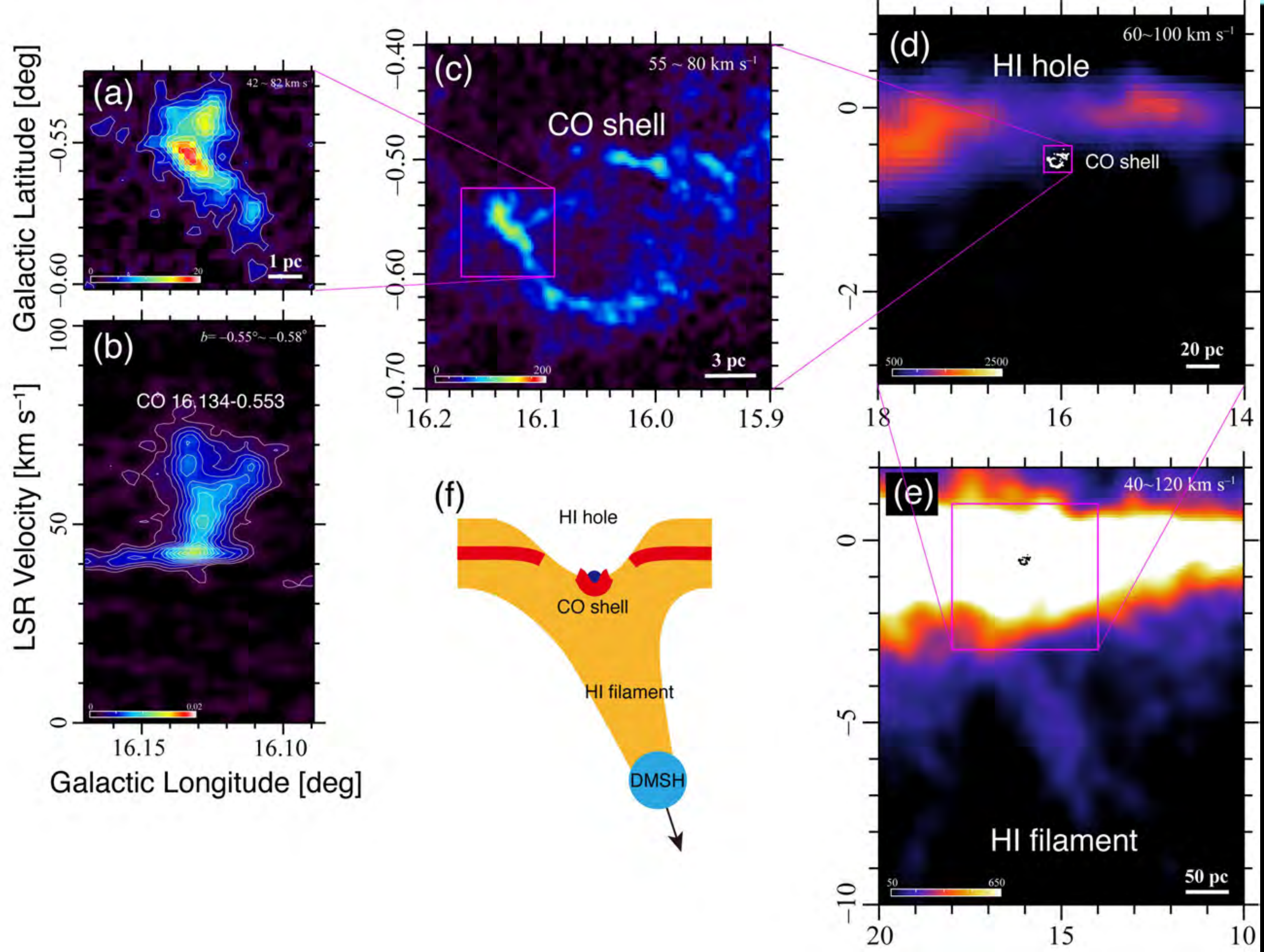
1. SUMMARY OF THE PROPOSAL(4)

- Threshold science mission
  - We believe that the plan is the minimum realistic one. Thresholds:15 peer-reviewed papers a year, 5 papers with 30 citations over a five-year period, 3 hands-on tutorials a year (contribution to education).
- Cost estimation
  - About one hundred million Japanese Yen/year is assumed, including income from charged telescope time abd external budget
- Project Organization (~ 10 staff)



SCIENTIFIC OBJECTIVES
3.2. MILKY WAY GALAXY SURVEY (7BEE, FPGA, FOREST)

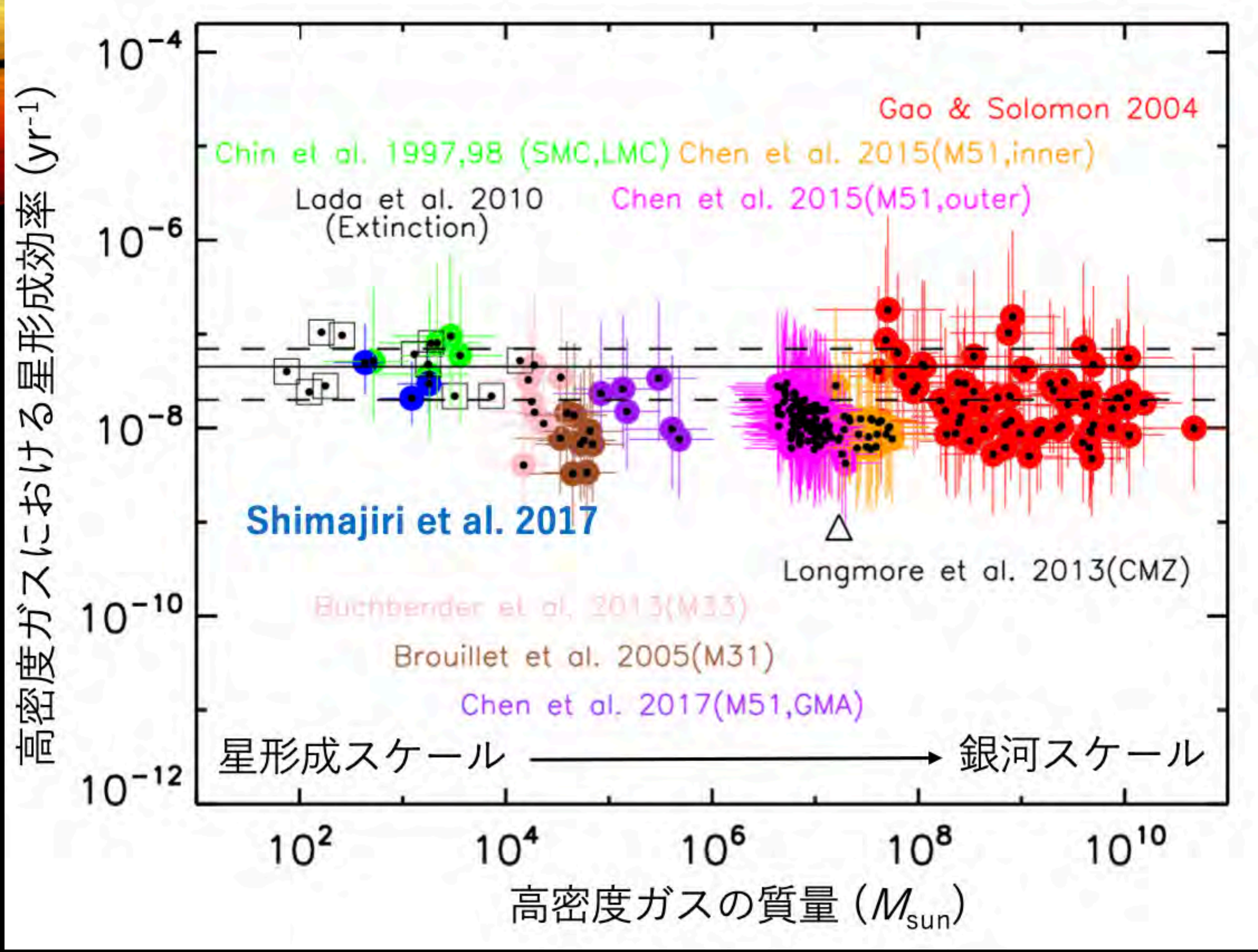
- The “Λ-CDM" model predicts that the dark matter halo surrounding a large galaxy is accompanied by many tiny dense regions (subhaloes) (e.g., Klypin et al. 1999; Moore et al. 1999): dark matter subhalos (DMSHs).
- We will search for high-velocity molecular gas components in CO J=1-0 and SiO J=2-1. This will help us understand the mass function on the low-mass side of DMSH, verify the Λ-CDM model, and provide clues about the nature of dark matter.
- This survey is also effective in detecting numerous "orphan black holes" (e.g., Yamada et al. 2017; Nomura et al. 2018).



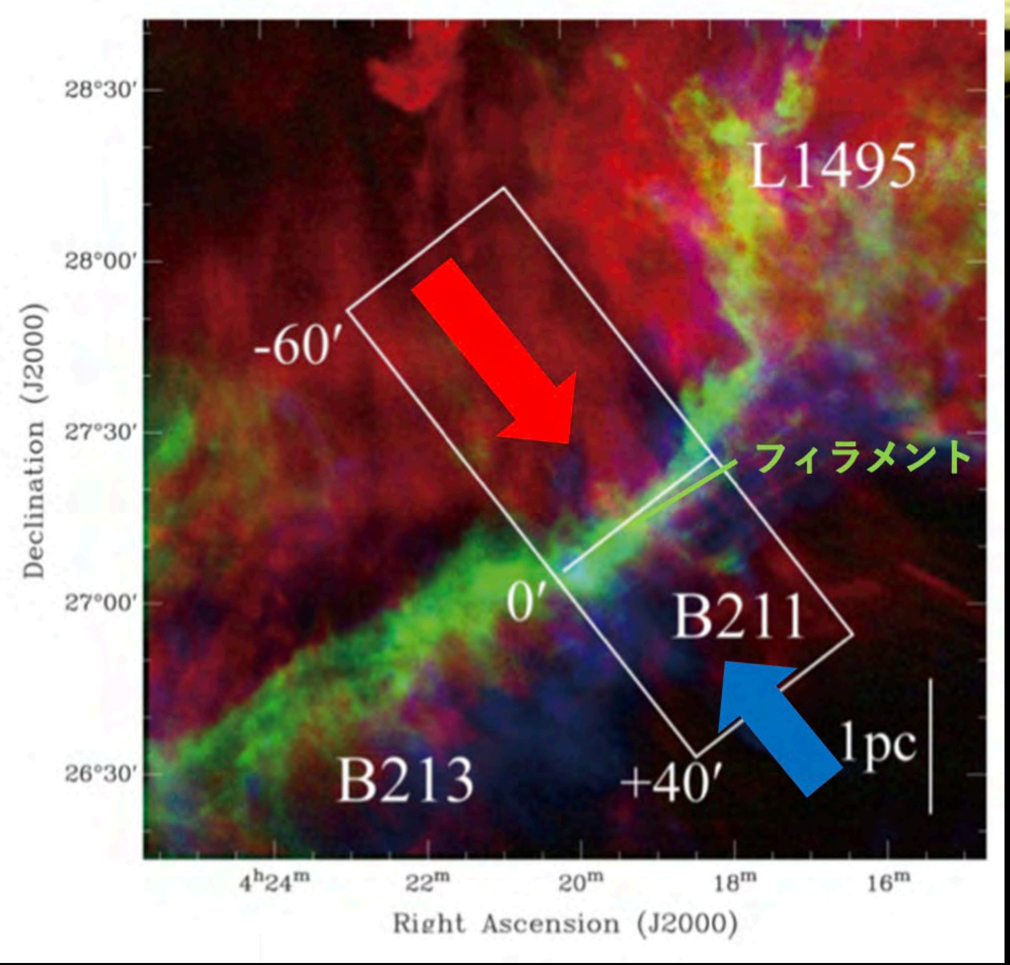
- Figure 3.1. (a) SiO J=2-1 integrated intensity diagram. (b) SiO J=2-1 l-v diagram. (c) CO J=1-0 integrated intensity diagram. (d)(e) HI 21cm integrated intensity diagram. (f) Schematic view of DMSH entry scenario.

3.3. FILAMENT FORMATION (7BEE, FPGA)

- Filaments with a width of 0.1 pc are common in nearby star-forming regions (Andre+10; Arzoumanian+11,19; Konyves+15).
- Star forming rate looks constant (Shimajiri+17) → studying filaments is essential to understanding star formation.
- In low-mass star-forming regions, entangled “fibers” with a 0.4 km/s vel difference were repotted (Hacar et al. 2013). Similar structures were also reported in massive star-forming regions (Shimajiri et al. 2019b). Further investigations in both low-mass and high-mass star-forming regions are needed to prove the universality of the filamentary star-forming scenario.
- These studies are expected to shed more light on the role that filaments play as the main stage for star formation



- Figure 3.2: Relationship between star formation rate in dense gas and mass of dense gas (Shimajiri et al. 2017)



- Figure 3,3: Ambient gas flowing into the filament in Taurus (Shimajiri et al. 2019a)

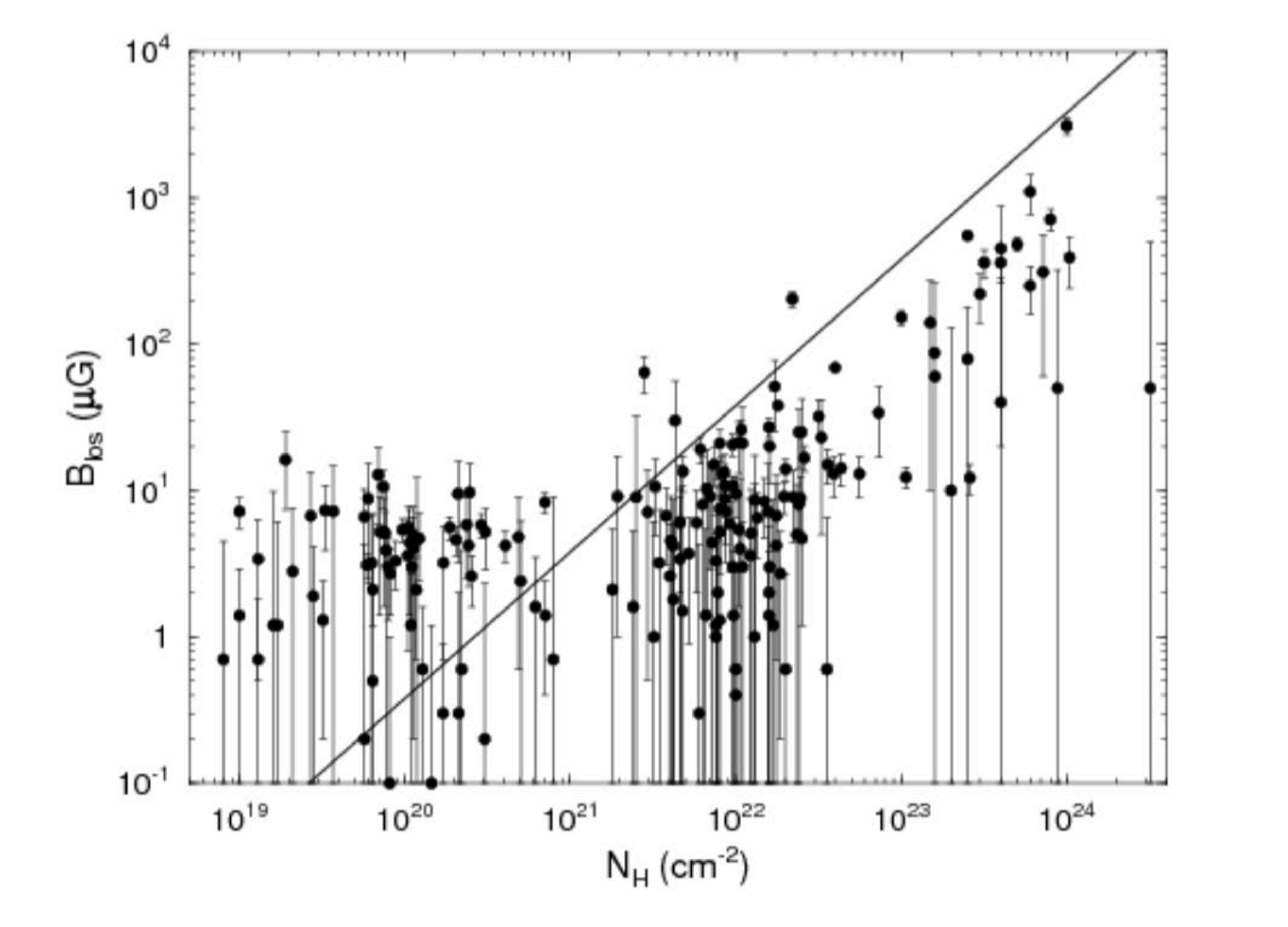
Figure 3.4: Artist's view of filament fragmentation to form a core (©National Astronomical Observatory of Japan, Shimajiri et al. 2023a)

3.4. CARBON CHAIN MOLECULES IN CLUSTER REGIONS (EQ)

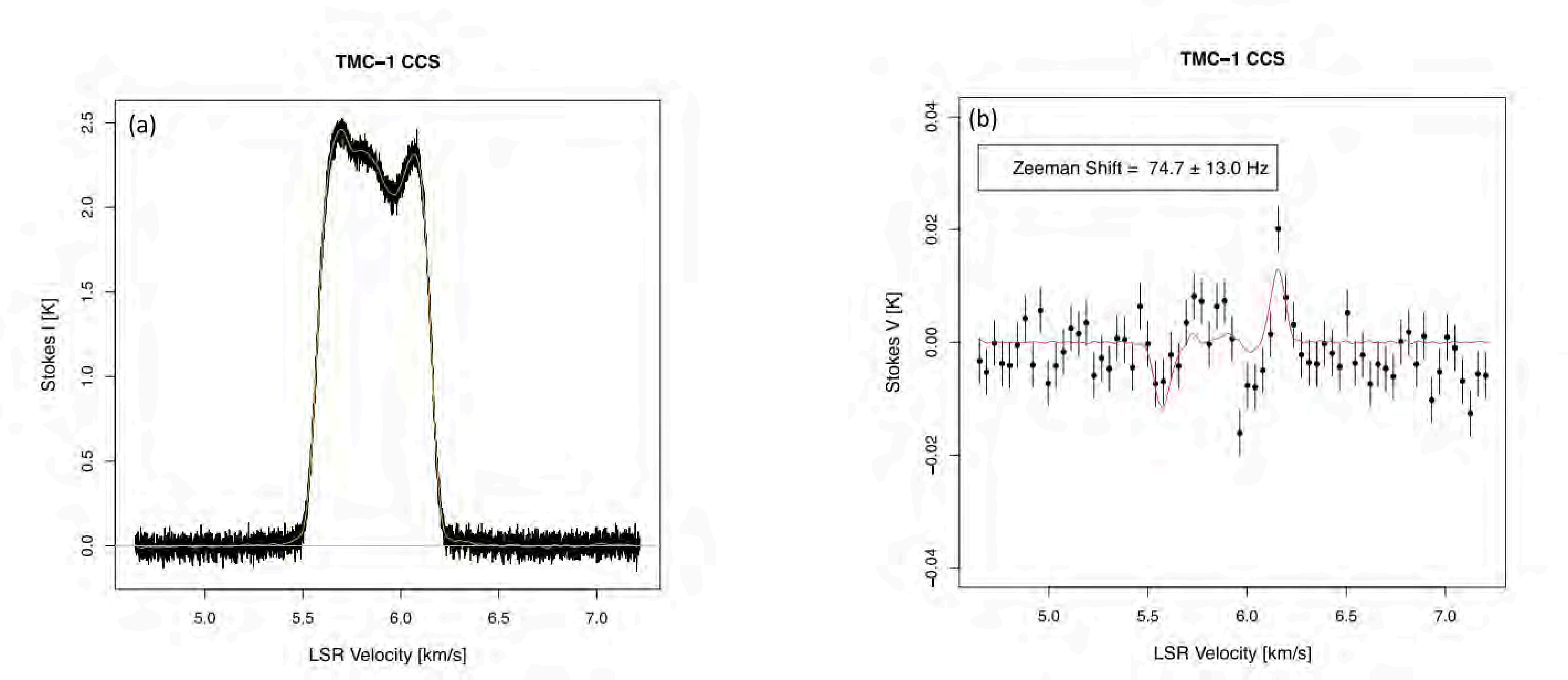
- Carbon chain molecules are good indicators of the evolutionary stage of starless clouds and cores. Because the solar system was born in a cluster region, it is important to know the chemical composition of the solar system in its early stages in cluster regions.
- Carbon chain molecules in starless clouds have wide spatial distributions, so observation using a single dish such as the Nobeyama 45 m telescope is essential to derive accurate chemical compositions.

3.6 ROLE OF MAGNETIC FIELDS IN MOLECULAR CLOUDS AND STAR FORMATION (EQ)

- The formation, kinematics, and evolution of the cloud core are mainly determined by the self-gravity, turbulence, and magnetic fields. Information on magnetic fields in star-forming regions has been limited.
- The most effective way is to observe the Zeeman effects. It is important to determine whether the cloud core is supercritical or subcritical.



- Figure 3.5: Column density and line-of-sight magnetic field strength estimated by Zeeman observations with HI/OH/CN. The solid line is the line of the magnetically critical state (state where self-gravity and magnetic field are balanced) (quoted from Crutcher 2012).



- Figure 3.6: Example of Zeeman observation at TMC-1 (CP) using Z45 receiver. The image on the right is the emission line profile (Stokes I profile) of CCS ($J_N=4_3-3_2$), and the image on the left is the Stokes V profile. From the fit of the Stokes V profile, the magnetic field strength was derived to be 117 microgauss (from Nakamura et al. 2019).

3.6 ROLE OF MAGNETIC FIELDS IN MOLECULAR CLOUDS AND STAR FORMATION (EQ)

- The process of star formation depends on the magnetic field strength, so accurate measurements are critical.
- The integration time with eQ will be four to five times shorter than the old Z45 receiver. Only CCS/SO Zeeman observations using eQ rare can solve the important problems of the dynamic role of the magnetic field.
- We can investigate the relationship between the strength of the magnetic field and the chemical composition of carbon chain molecules for the first time.

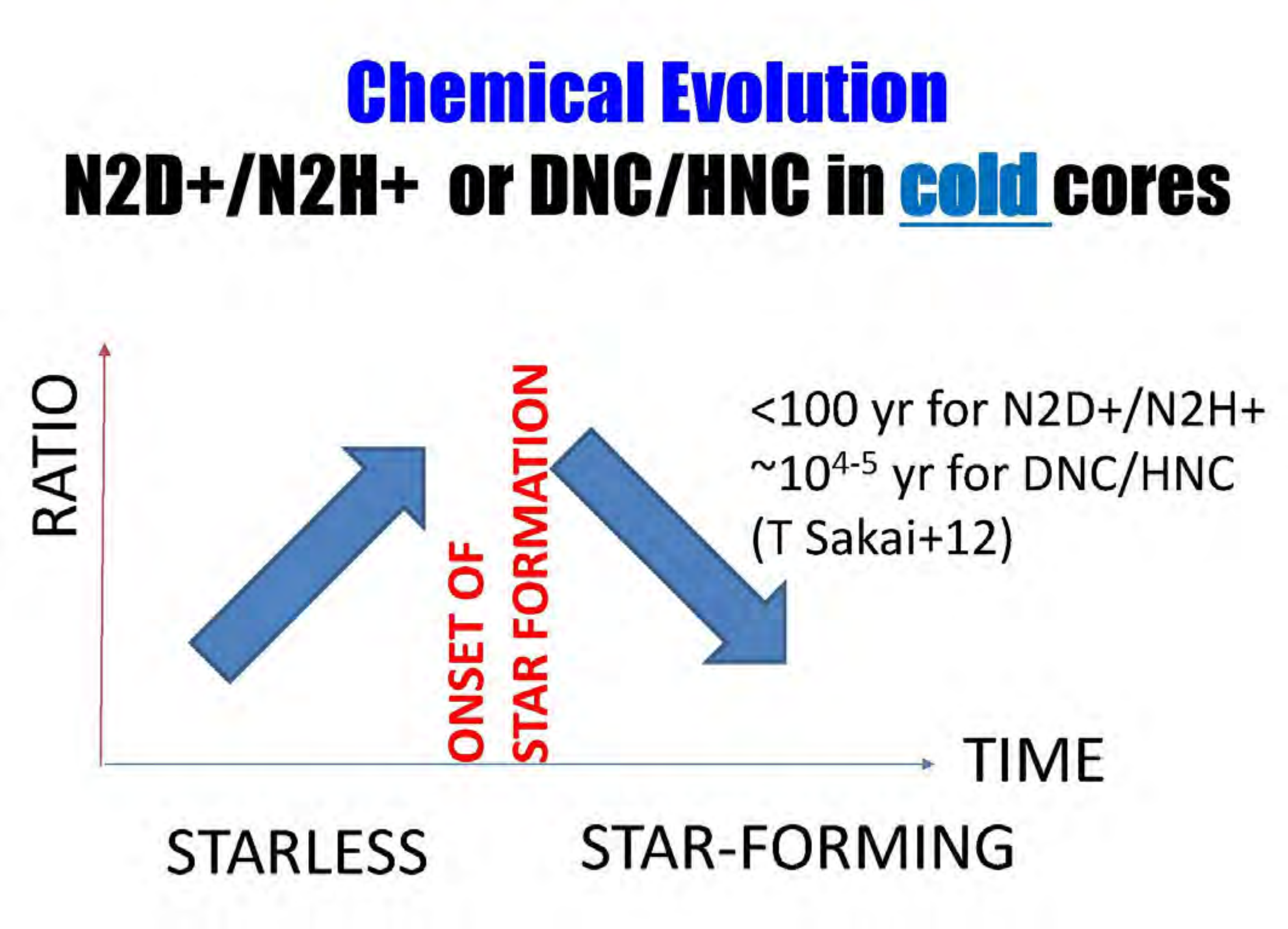
3.7 HIGH REDSHIFT OBJECTS (EQ)

- It is known that z = 2-3 was the period of the most active star formation.
- CO is the most abundant molecule after molecular hydrogen. Emission lines in the range z=1.30-2.83 for CO (J=1-0) and z=3.60-6.67 for CO (2-1) can be observed with eQ.
- Such measurements can be achieved with interferometric observations such as ALMA/VLA, but single-dish observations are useful for estimating the total amount of molecular gas without resolving-out.

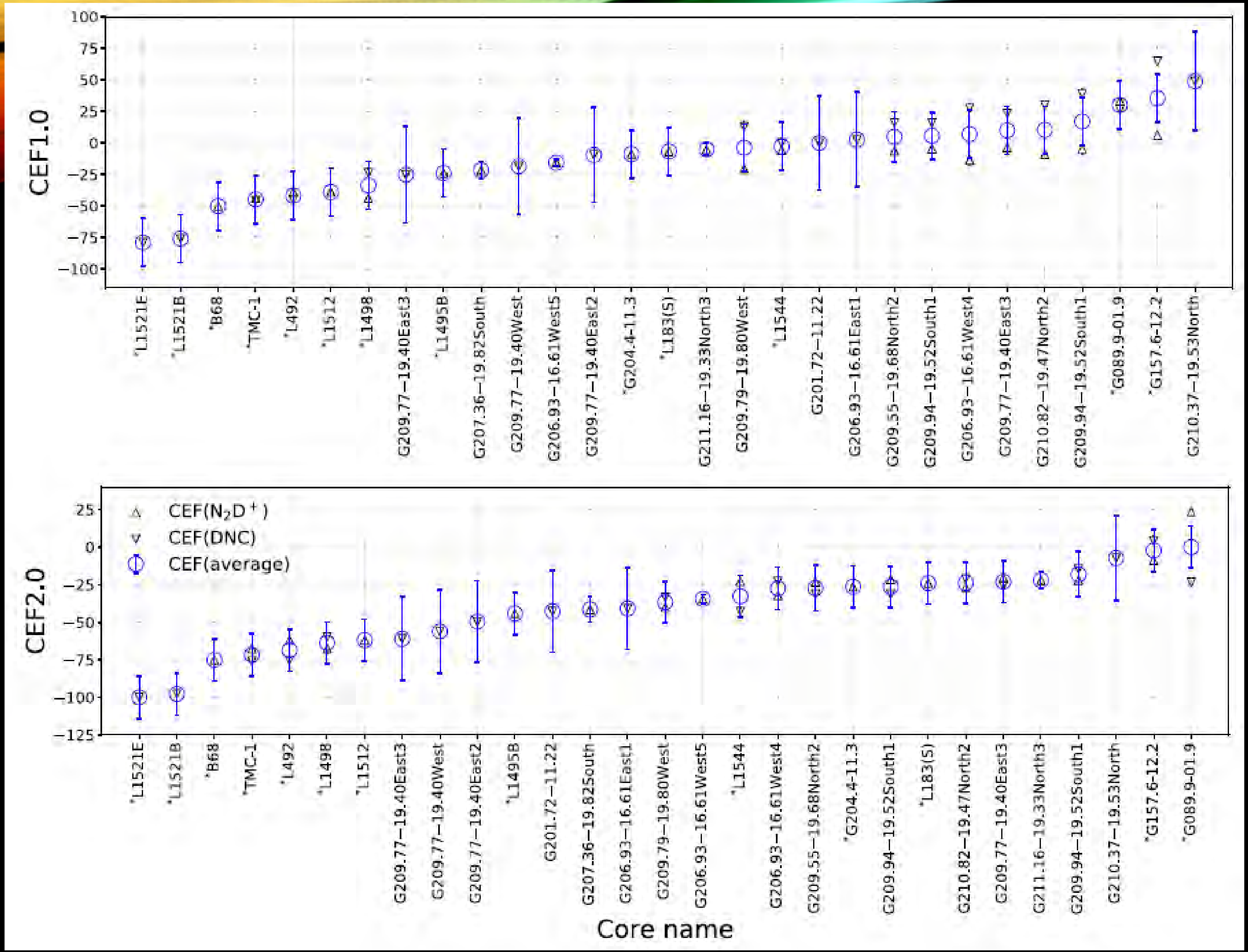
3.8 STARLESS CLOUD EVOLUTION BASED ON THE DEUTERIUM FRACTION

(7BEE, FPGA)

- Deuterated molecules are becoming important for studies of starless cores
  - depletion of molecules are serious for starless cores: N2D+, which is less depleted, is found to be a powerful tracer
  - deuterated molecules can be used as an evolutionary tracers of starless cores
- We developed a new measure, **Chemical Evolution Factor (CEF)** based on the deuterium fraction (Tatematsu+17; Kim+20)
- It is expected that observations with deuterated molecules will elucidate the process from the cloud core to the protostar.



- Figure 3.7 Schematic diagram of deuterium fraction evolution in a low-temperature molecular cloud core



- Figure 3.8: Chemical Evolution Factor (CEF) based on the D/H. Version 1.0 by Tatemastu et al. (2017) and Version 2.0 by Kim et al. (2020). The farther to the right you go, the closer to the onset of star formation.

- Collaboration with ALMA is essential.

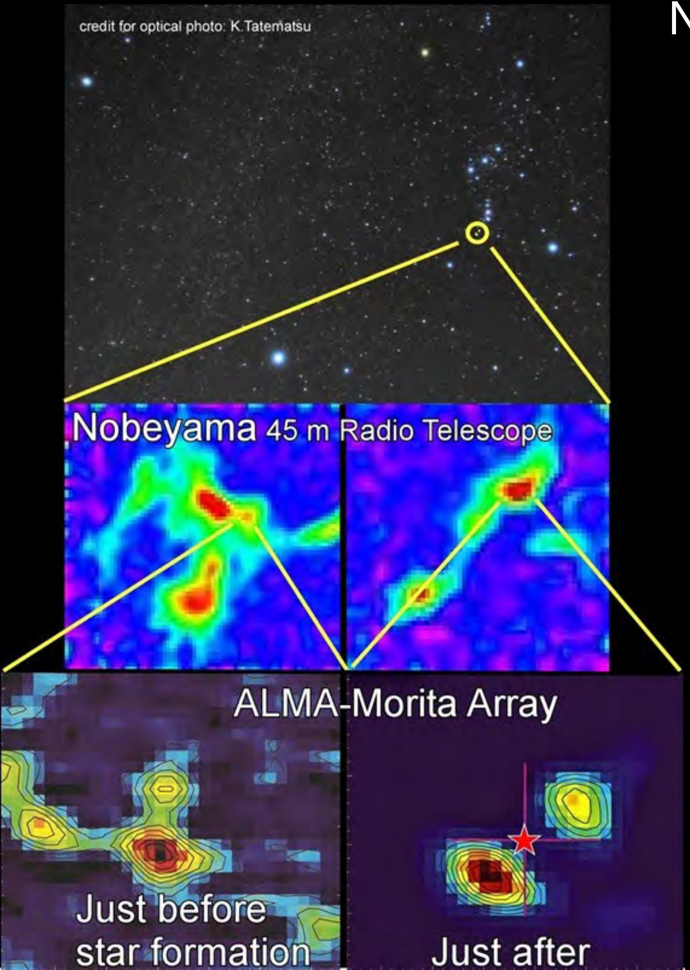


Figure 3.9: Just before and after star formation. Middle panel) Nobeyama 45 m telescope, Low panel) ALMA (Tatematsu+20).

Observations of deuterated molecules will elucidate the process from the cloud core to the protostar.

3.9. VLBI OBSERVATION(1)

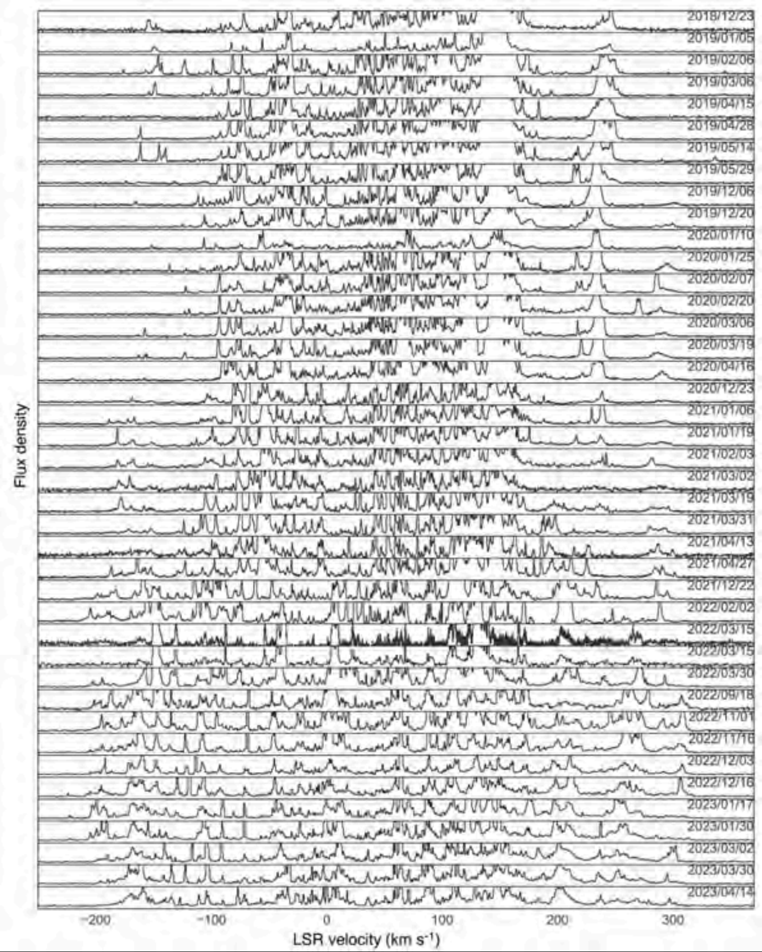
- AGN mass accretion
  - the mass accretion process near the SMBH.
  - the unique structure of Sgr A* through monitoring observations.
- Mechanism of AGN jet formation and acceleration
  - velocity field measurements of M87 jet at <100-10000 Schwarzschild radii.
- Origin of interstellar condensation
  - we will image the HCN and HCO+ absorption lines against the QSO

3.9. VLBI OBSERVATION(2)

- massive star formation
  - 3D motion of these maser spot groups, which will make clear the formation and development process of massive stars.
- AGB star mass ejection
  - 22/43/86 GHz simultaneous monitor for H2O and SiO maser sources will help to understand the excitation mechanisms, the time variation, the AGB star evolution, and the origin of various shapes of planetary nebulae.

3.10. TIME-DOMAIN ASTRONOMY

- we can understand the nature and evolution of the celestial body that caused the event. In particular, rapid brightening and jet formation will be observed in merger events involving rapid accretion on compact ultra-dense objects such as black holes
- Feasibility was confirmed using the H_2O maser (Imai et al. 2023, see next slide). The 45m telescope is one of the high-sensitivity telescopes that can simultaneously monitor SiO masers (Amada et al. 2022) and H_2O masers
- Monitoring of multiple CH_3OH maser → changes in the physical state of the circumstellar matter due to the accretion onto the massive star.

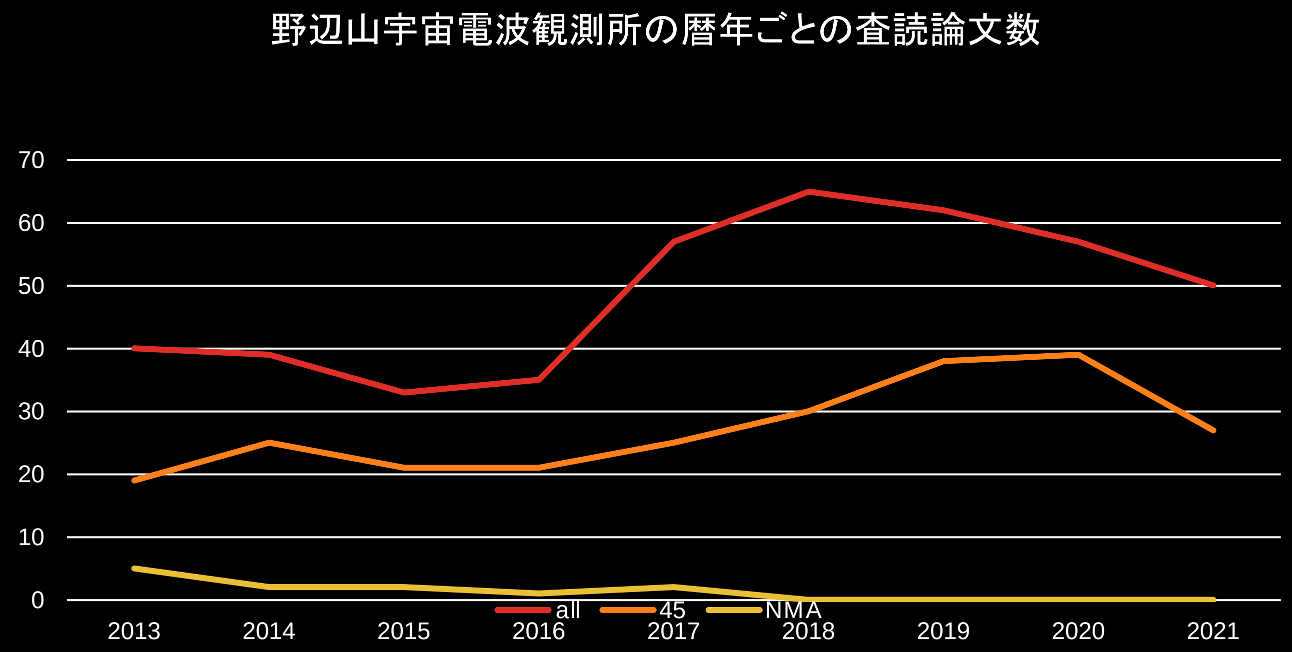


- Figure 3.11: Time-series spectra of the H2O maser associated with the "cosmic fountain" object IRAS 18286-0959, obtained during monitoring observations with the Nobeyama 45 m telescope (Imai et al. 2023).

PRODUCTIVITY: REFEREED PUBLICATION

30-40 refereed papers/yr

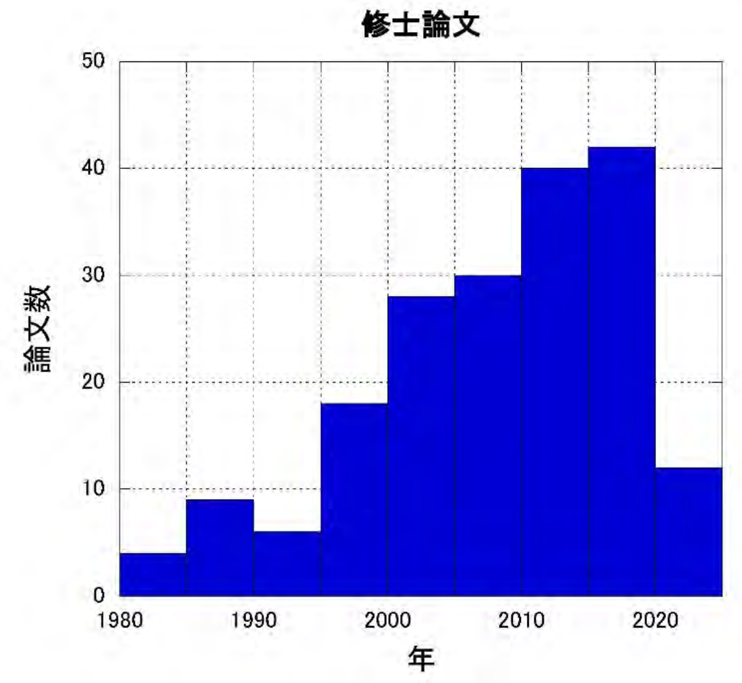
See the orange line for the 45 m telescope publication



- Figure 3.12 Number of peer-reviewed papers. Data for 2021 is incomplete (up to September 18th).

EDUCATION: NUMBER OF MASTER AND PHD THESES

8 master theses/yr



- Figure 3.13 Number of master's theses. The 2020-2024 bin is incomplete (only 2020-2021).

3 PhD theses/yr

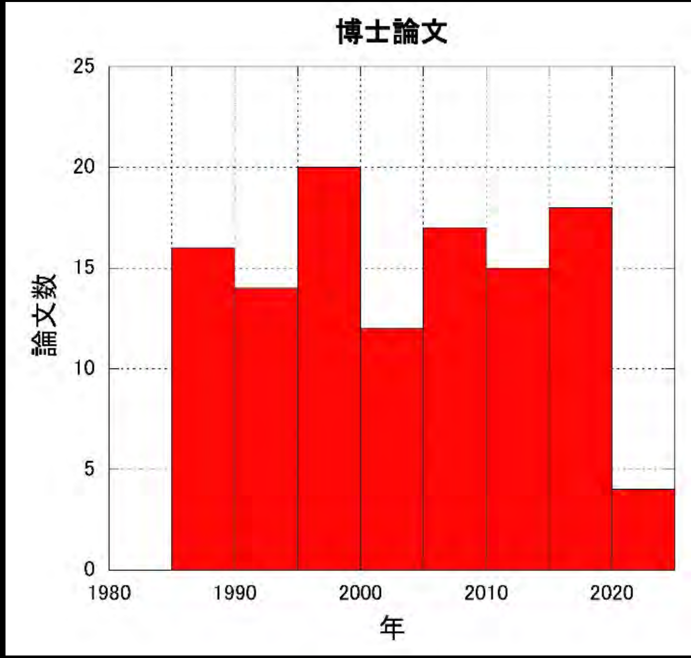


Figure 3.14 Number of doctoral theses. The 2020-2024 bin is incomplete (only 2020-2021).

5. INSTRUMENTS AND DATA TO BE RETURNED

- Nobeyama 45m radio telescope, eQ receiver, 7BEE receiver (under commissioning) , and new spectrometers using FPGA (new development).

eQ receiver (with ASIAA)

7BEE receiver (with OMU and ALMA Project)

All data will be made public 3 years after observations

6. OPERATIONS

- The charged telescope time that started in 2022 will continue (10,000 yen + tax per hour for PIs affiliated with domestic institutions, 30,000 yen + tax per hour for others).
- We continue Nobeyama Development Programs.
  - Can be a test bench for future Radio Astronomy: ALMA2, ngVLA, LST, Antarctic THz telescope etc.
- Overall operation cost: ~1 M$/yr ~ 100 M Yen/yr ~1.0億円/年
- We assume
  - ~ 0.75 M$/yr from Unko-kin 運交金
  - ~ 0.20 M$/yr from charged telescope time 有料望遠鏡時間
  - ~ 0.05 M$/yr from Kakenhi 科研費

- (FYI We earned 0.35 M$=3500万円 in FY2022 through charged telescope time. Can be beginner's luck. We list a conservative estimate above.)

7. RATIONALE AND TRADE-OFF STUDIES

- ALMA is overwhelming, but ALMA alone is not enough. For starless cores, the missing flux may exceed 80% even when using ACA (Tokuda et al. 2020, ApJ, 899, 10).
- The mapping speed of deuterated molecules with 7BEE is among the highest in the world even without the new spectrometers (we got the largest single dish map of the deuterated molecules, as reported at the 2022 Spring ASJ meeting tenmon-gakkai), and we expect that 7BEE will achieve unparalleled performance worldwide with the new spectrometers.

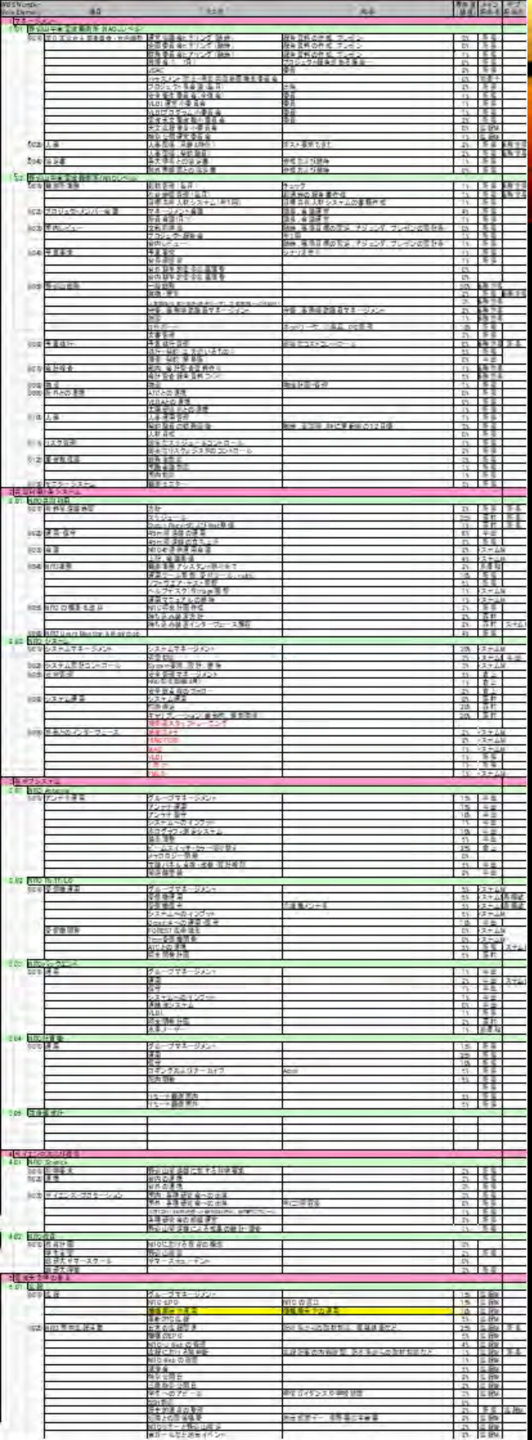
8. SCIENTIFIC TRACEABILITY MATRIX

Table: Science traceability matrix

Science goals	Science objectives	Investigations		Instruments		Data requirements
		Physical parameters	Observables	Design Parameters	Requirements	
15 refereed papers or more per year	Elucidating the hierarchical structure of molecular clouds, the evolution of molecular clouds, the mysteries of star formation rate, and the role of magnetic fields in star formation Star formation research based on dating of molecular cloud cores	Refereed paper numbet	Paper number	15/year	15/year	
		Citation	citation number	5 papers over a five-year period	5 papers over a five-year period	30 citations or more
Hands-on Tutorial Observations	Provide opportunities of radio telescope observation for undergraduate students and graduate students			3 times/year	3 times/year	

- See 9 Thredshold Science (next slide)

- 9. Threshold Science
  - 15 peer-reviewed papers a year.
  - Five papers with 30 citations over a five-year period.
  - Three hands-on tutorials a year (contribution to education).
  - (We avoid to list specific quantitative science targets, because charged telescope time assumes equal opportunities rather than bias to a specific group)
- 14. Acquisition surveillance: make or buy
  - Purchased HEMT using InP (we originally planned to get from U. Manchester under collaboration, but due to the coronavirus pandemic, we purchased from Low Noise Factory instead) **under commissioning**
  - Developed an optimized input optical system including anti-reflection (complete)
  - Developed frequency separation using frequency separation triplexer (complete)
  - spectrometer using FPGA (to be built with an external budget)



16. WORK BREAKDOWN STRUCTURE (WBS)

WBS Number Work Element	項目	タスク	内容	専有度（頻度）	メイン担当者	サブ担当者
1	マネージメント					
1 .01	野辺山宇宙電波観測所（NAOJレベル）					
0010	国立天文台主要委員会・台内調整	運営協議会ヒアリング（随時）	報告資料の作成、プレゼン	0%	所長	
		企画委員会ヒアリング（随時）	報告資料の作成、プレゼン	0%	所長	
		財務委員会ヒアリング（随時）	報告資料の作成、プレゼン	1%	所長	
		教授会（1、7月）	プロジェクト報告がある場合…	0%	所長	
		JSAC	委員	2%	所長	
		ハラスメント防止・男女共同参画推進委員会		0%	宮澤千	
		プロジェクト長会議（毎月）	出席	2%	所長	
		安全衛生委員会（全体会）	委員	1%	所長	
		VLBI 運営小委員会	委員	1%	所長	
		VLBIプログラム小委員会	委員	1%	所長	
		電波天文周波数小委員会	委員	2%	所長	
		天文広報普及小委員会		0%	広報M	
		特別公開運営委員会		1%	広報M	
0020	人事	人事関係（承継&特任）	ポスト要求も含む	2%	所長	事務室長
		人事関係（契約職員）		2%	所長	事務室長
0040	協定書	各大学等との協定書	作成および維持	1%	所長	
		諸外国期間との協定書	作成および維持	0%	所長	
1 .02	野辺山宇宙電波観測所（NROレベル）					
0010	観測所業務	超勤管理（毎月）	チェック	1%	所長	事務室長
		在台時間管理（毎月）	超過時の報告書作成	1%	所長	事務室長
		目標共有人材システム（年1回）	目標共有人材システムの書類作成	1%	所長	
0020	プロジェクトメンバー会議	マネージメント会議	議長、会議運営	4%	所長	
		所員会議（月1）	議長、会議運営	1%	所長	
0030	国内レビュー	文部科学省	随時、獲得目標の設定、アジェンダ、プレゼンの設計等	0%	所長	
		プロジェクト報告会	年1回	1%	所長	
		台内レビュー	随時、獲得目標の設定、アジェンダ、プレゼンの設計等	1%	所長	
0040	予算要求	予算要求	シナリオ作り	1%	所長	
		台長留置金		1%	所長	

- END