

# Building a New Era for ALMA Science

1. How ALMA has established the roadmap for the next decade
2. What was the process in Japan to realize it ("ALMA2")

Misato Fukagawa, ALMA Project

slides from Alvaro Gonzalez (NAOJ), John Carpenter (Joint ALMA Observatory)

NAOJ Future Planning Symposium 2023, November 7, 2023



# Science Requirements in the construction phase

## Requirement 1 (Origin of Galaxies)

Detect spectral line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of  $z=3$ , in less than 24 hours of observations.

## Requirement 2 (Origin of Planets)

Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc

## Requirement 3 (High Angular Resolution/Origin of chemical complexity)

The ability to provide precise images at an angular resolution of  $0.''1$ . Reveal the chemical evolution in the universe

During the ALMA International Review in 2019, it was assessed that these requirements had been basically met

How can ALMA continue to be the world's leading telescope for astronomy?

(modified from the original slide)





# ALMA2030 Report by ALMA Science Advisory Committee

In 2015, ASAC examined **potential technical developments** for ALMA between then and the year 2030. The **ASAC recommended**, with no specific priority, four development paths based on their long-term scientific potential:

1. Improvements to the **Archive**: enabling gains in usability and impact for the observatory
2. **Larger bandwidths and better receiver sensitivity**: enabling gains in speed
3. **Longer baselines**: enabling qualitatively new science
4. Increasing **wide field mapping speed**: enabling efficient mapping

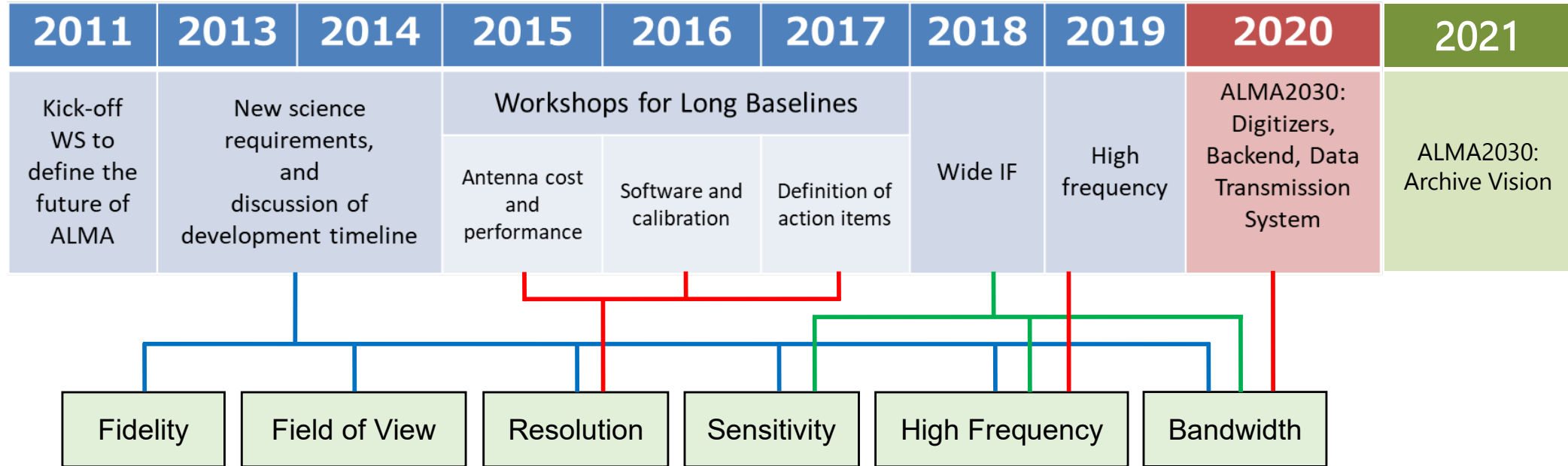
In November 2015, in order to review and prioritize the recommendations from ASAC, ALMA formed a **Development Working Group** with the tasks to:

- Propose a **science-driven prioritization** for the medium to longer-term developments
- Propose **new science goals** for the upcoming decade





# We have been thinking for a long time in Japan and East Asia



In EA, the input of the community is received annually in the EA Development Workshop. In 2011-2014, we defined the science requirements from the EA community which were fed back into the ALMA Development Roadmap (ADR). From 2015, we have discussed particular priorities in detail, and the actual technical implementation of the ADR.



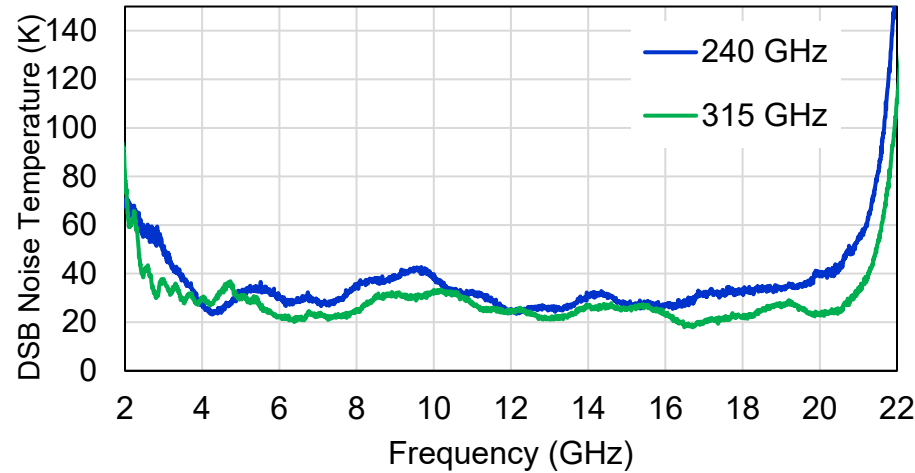
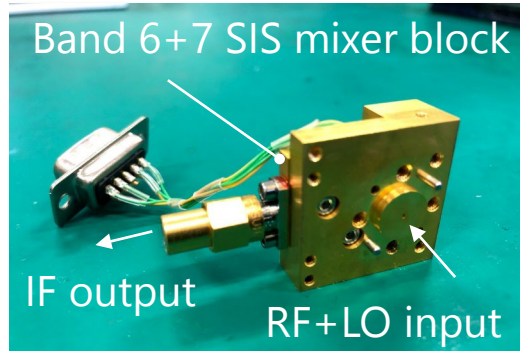
Workshop on wideband receivers (Osaka, 2018)





# We have been thinking for a long time in Japan and East Asia

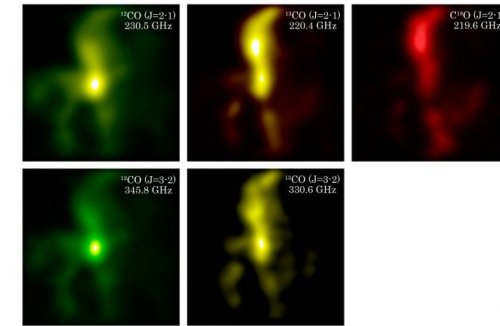
## Wideband receivers



NAOJ ATC in collaboration with multiple institute/universities

Kojima et al. (2020), Masui et al. (2021), Yamasaki et al. (2021) 他

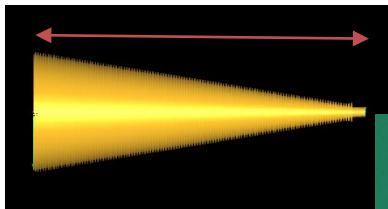
Test observations with the 1.85m telescope of Osaka Kohritsu U.



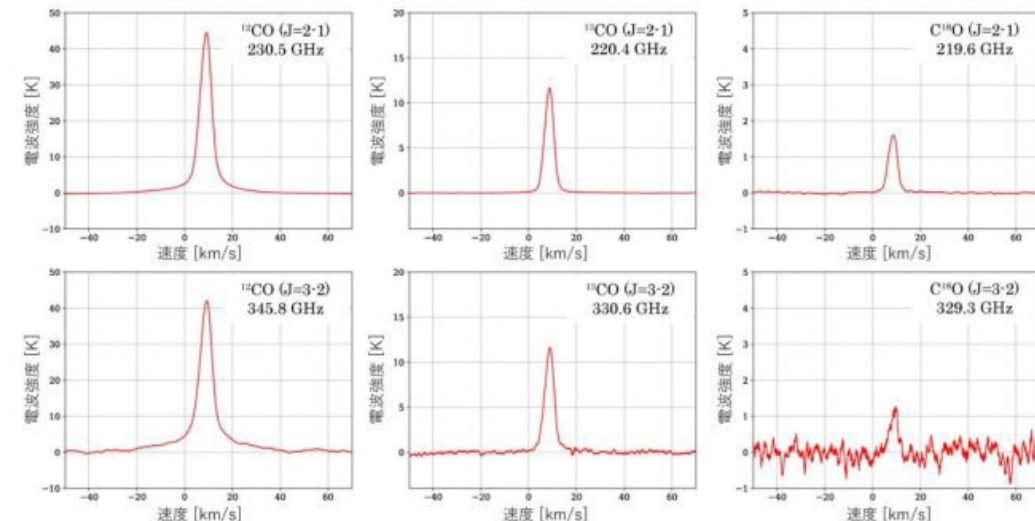
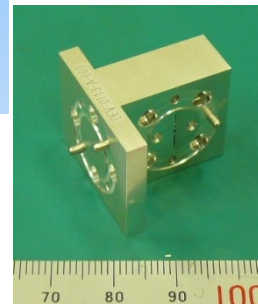
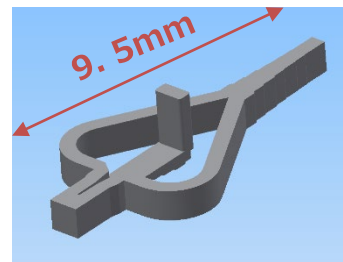
## Band 8 upgrade

Corrugated horn

22.867 mm



OMT



2024/3/8





# Delivery of ALMA Development Roadmap

The outcome was released as the ALMA Development Roadmap in 2018.



## New Science goals



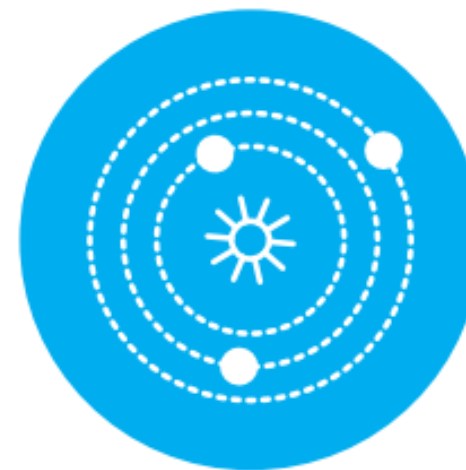
### ORIGINS OF GALAXIES

Trace the cosmic evolution of key elements from the first galaxies ( $z > 10$ ) through the peak of star formation ( $z = 2-4$ ) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.



### ORIGINS OF CHEMICAL COMPLEXITY

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales ( $\sim 10-100$  au) by performing full-band frequency scans at a rate of 2-4 protostars per day.



### ORIGINS OF PLANETS

Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone ( $\sim 1$  au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.





# Delivery of ALMA Development Roadmap

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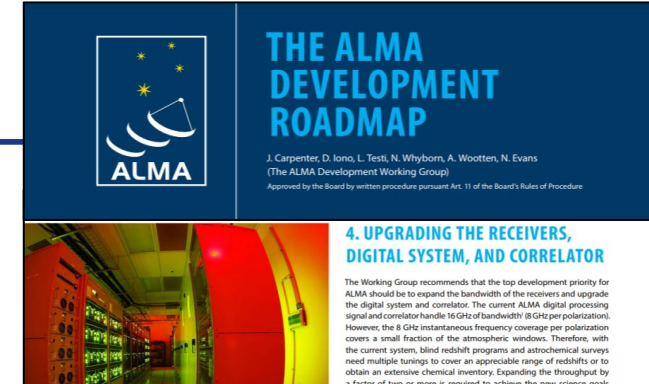
## Development priority

1. Broaden the receiver IF bandwidth by at least a factor two, and to upgrade the associated electronics and correlator.
2. A group should be tasked with prioritizing the long-term capabilities of the ALMA archive.



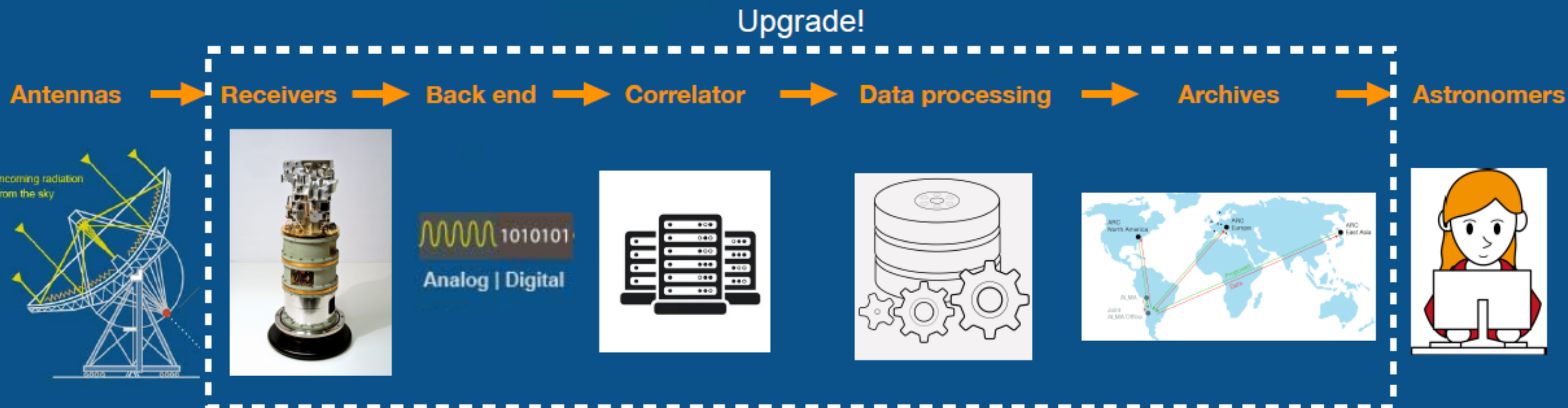
## Wideband Sensitivity Upgrade

- Available bandwidth : factor of 2-4 increase
- Correlated bandwidth : more than an order of magnitude increase with  $\sim 0.1$  km/s resolution
- Observing speed : 2.2-4.7x faster for spectral lines, 4.8x faster for continuum (in the example case of Band 6v2)



# Wideband Sensitivity Upgrade (WSU)

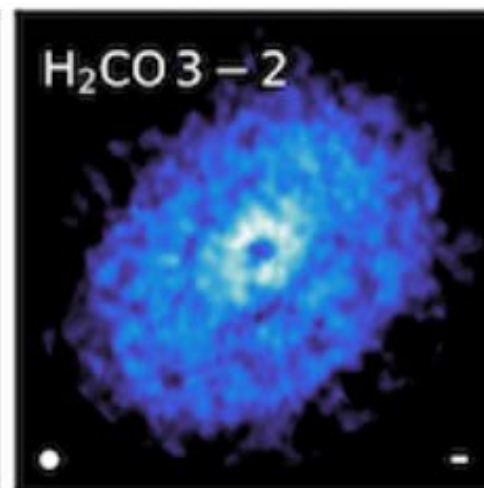
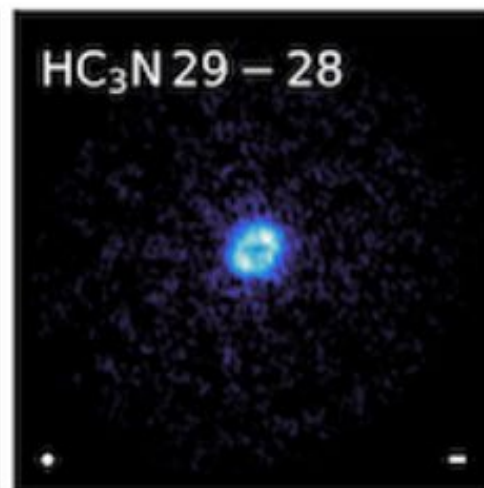
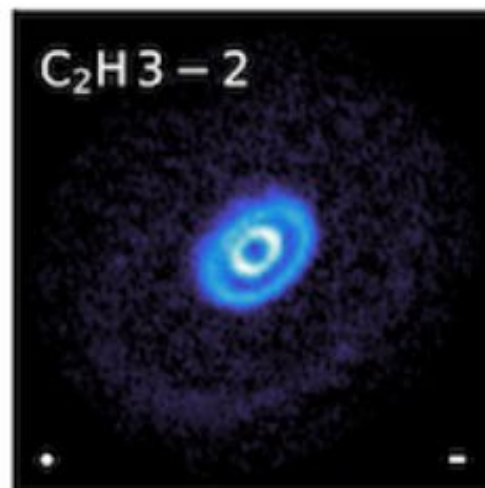
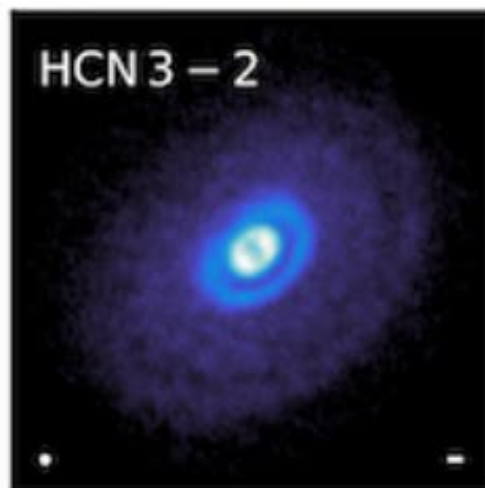
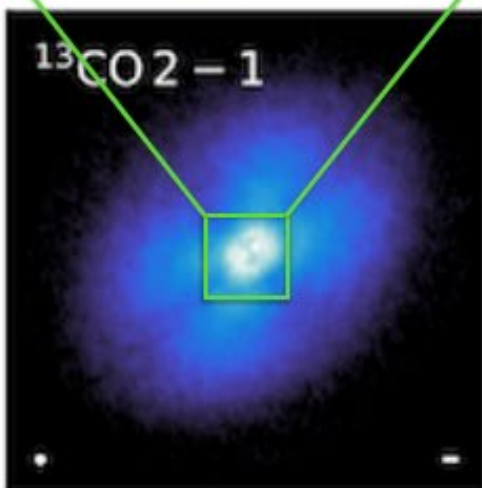
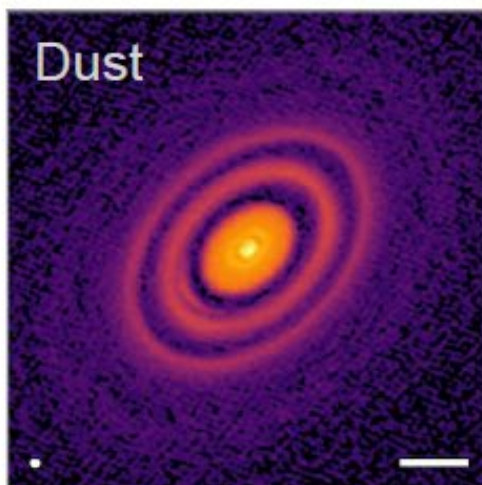
- Upgrade of the bandwidth and throughput of the ALMA system
  - upgraded receivers with increased bandwidth and improved receiver temperatures
  - more powerful correlator
  - increased data reduction capacity





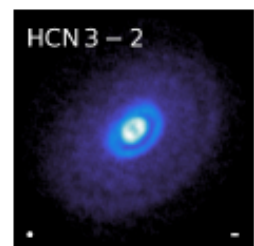
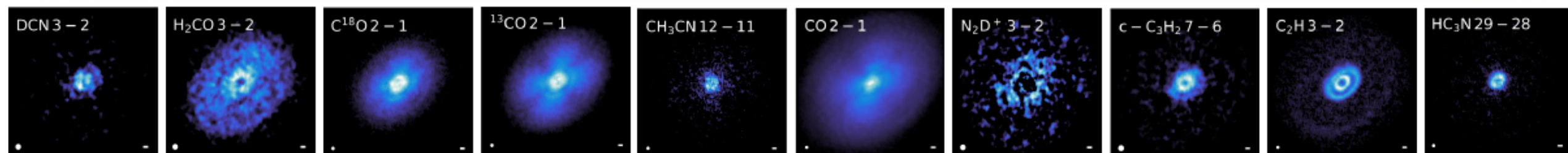
# The power of molecular spectroscopy in disks

HD 163296



- Gas mass
  - dust traces only  $\sim 1\%$  of the total disk mass
  - use molecules to trace the dominant disk component ( $\text{H}_2$ )
- Chemistry and the chemical compositions of planets
- 3D velocity and temperature structure of disks
- Detect embedded planets through velocity distortions
- **With vastly improved spectral grasp and improved line (and continuum!) sensitivity, the Wideband Sensitivity Upgrade will be a tremendous advance for disk studies.**

# The WSU Advantage



— DCN  $J = 3 - 2, F = 2 - 2$   
 —  $\text{H}_2\text{CO } 3(0, 3) - 2(0, 2)$   
 —  $\text{C}^{18}\text{O } J = 2 - 1$   
 —  $^{13}\text{CO } J = 2 - 1$   
 —  $\text{CH}_3\text{CN } 12(3) - 11(3)$

— CO  $J = 2 - 1$   
 —  $\text{N}_2\text{D}^+ J = 3 - 2$

MAPS (2 tunings)

—  $\text{c-C}_3\text{H}_2 \ 6(2, 5) - 5(1, 4)$   
 —  $\text{c-C}_3\text{H}_2 \ 7(0, 7) - 6(1, 6)$

—  $\text{C}_2\text{H } N = 3 - 2, J = 5/2 - 3/2$

—  $\text{HC}_3\text{N } J = 29 - 28$

—  $\text{HCN } J = 3 - 2$

210

220

230

240

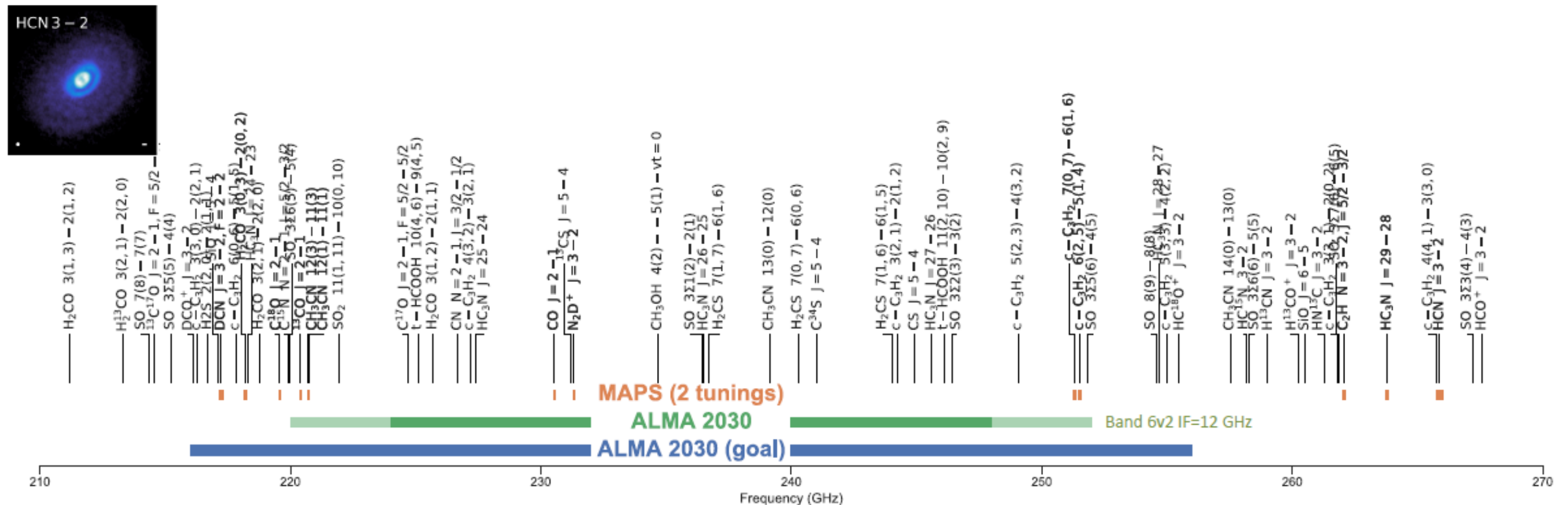
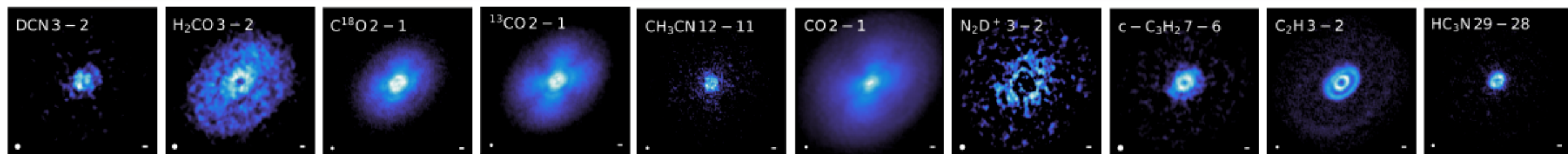
250

260

270

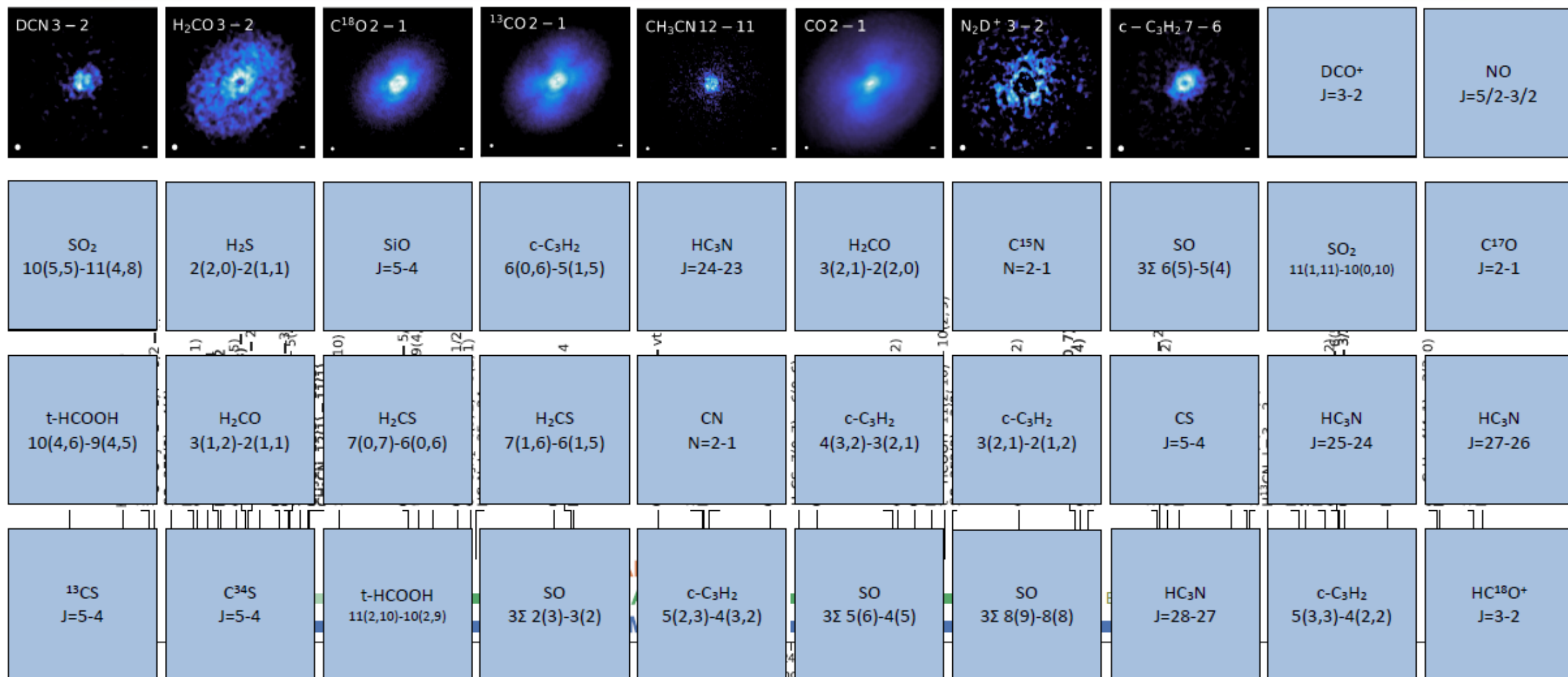
Frequency (GHz)

# The WSU Advantage





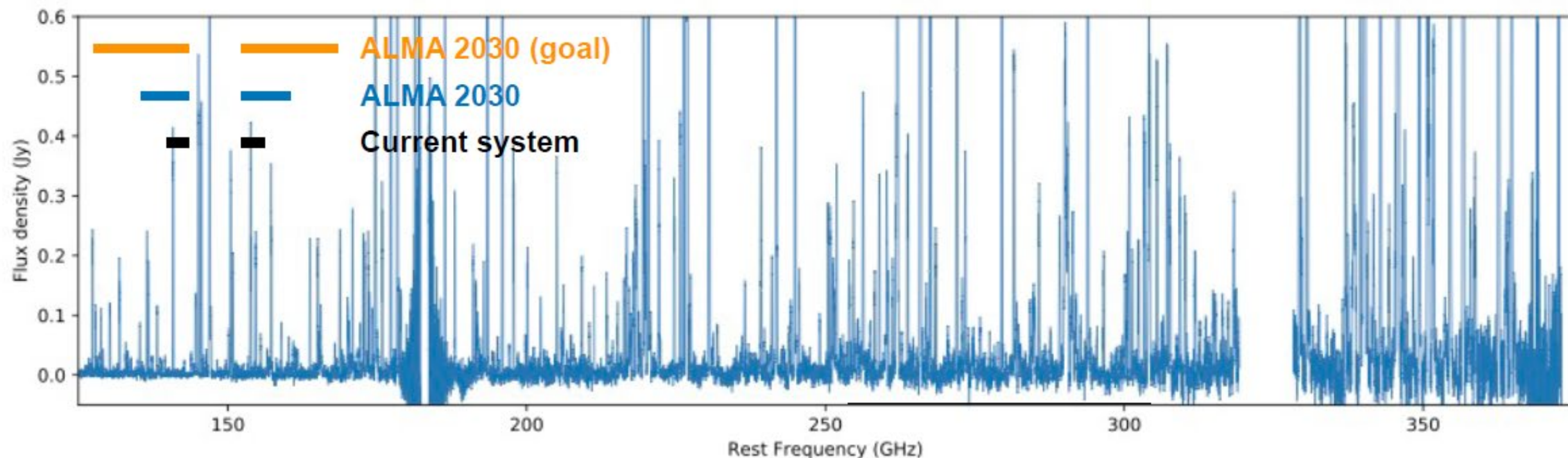
# The WSU Advantage



... and up to 40 additional spectral windows!

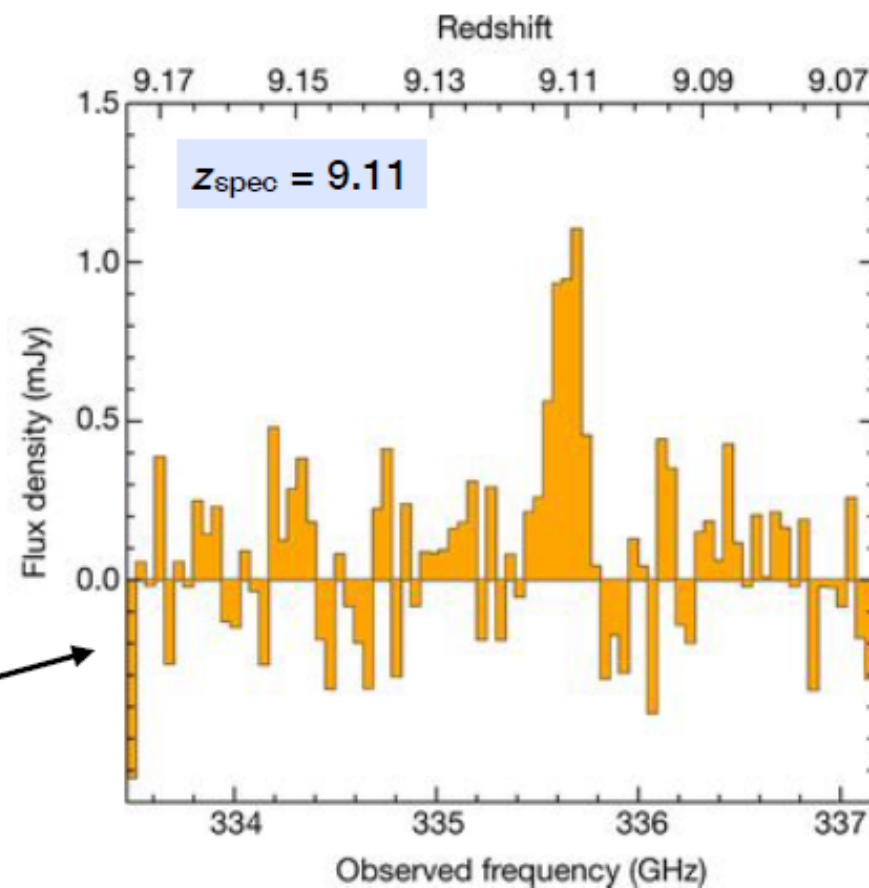
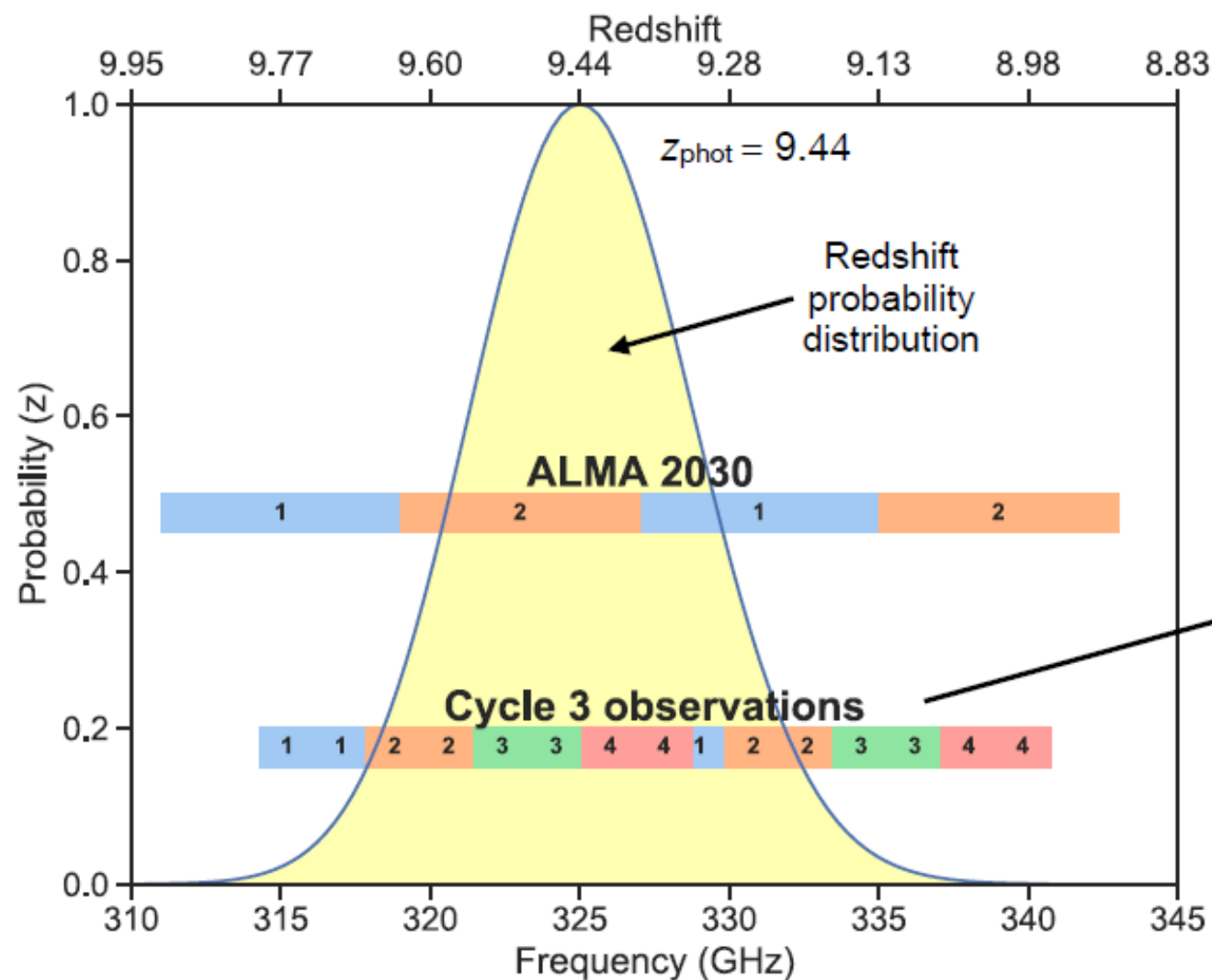


# ALCHEMI survey of NGC 253



- Survey speed with ALMA 2030 will increase by a factor of 3-6 plus any gains from improved receiver temperatures.

# ALMA spectral scan search for Oxygen in MACS1194-JD



- ALMA 2030 upgrade will be at least 3 times faster plus any improvements from lower receiver noise



# What is ALMA2?

## ALMA Development Roadmap (2018)



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**ALMA2** is the name used in Japan referring to the plan to carry out the **major upgrades** defined in the Development Roadmap and to provide the new observing capabilities to the research community, at the same time we continue operations of the ALMA telescope.

## ALMA2 Project (2019)



<https://alma-telescope.jp/publish>







# ALMA2 from April 1<sup>st</sup> in 2023

"Atacama Large Millimeter/submillimeter Array 2 (ALMA2) in Search of Our Cosmic Origins" (FY2023-2032)  
「宇宙と生命の起源を探究する大型ミリ波サブミリ波望遠鏡アルマ 2 計画」(2023～2032年度)

## Background

ALMA is being operated in the framework of the Large-scale Academic Frontier program by MEXT in Japan. **The current ALMA project period will end in FY2022.** ALMA had to be selected in the MEXT Roadmap to be implemented in the Frontier program in order to continue the operations.

ALMA計画は大規模学術フロンティア促進事業で実施している。現在の計画期間は2022年度で終了する。ALMAの運用を継続するには、文部科学省ロードマップに掲載され、大規模学術フロンティア促進事業に選定される必要がある。

January 2020: **Selected** as one of the high priority projects  
**in the Master Plan 2020** by the Science Council of Japan  
September 2020: **Selected in the MEXT Roadmap 2020**

2020年1月：日本学術会議マスタープラン2020に重点大型研究計画として掲載  
2020年9月：文部科学省ロードマップ2020に掲載

Scientific achievements so far by the community was a strong endorsement.  
Reflected also in the endorsement by the Community in the MP2020.

After a successful transition review in 2022, ALMA2 has received endorsement by MEXT Committee to start from April 1<sup>st</sup> 2023



[https://www.mext.go.jp/content/2022\\_0728-mxt\\_gakkikan-000025951\\_1.pdf](https://www.mext.go.jp/content/2022_0728-mxt_gakkikan-000025951_1.pdf)







# Standing on the huge efforts so far

Continuation of ALMA2 is based on the huge efforts by many people so far: management, development, engineering, operations, scientists



## アルマ望遠鏡の沿革—計画立案

年	日本学術会議	宇宙電波懇談会	日本	米国（北米）
1982			野辺山宇宙電波観測所の観所	
1983			大型ミリ波干渉計（LMA）構想	ミリ波干渉計（MMA）構想
1984				
1985				
1987			サブミリ波の本格観測を視野に入れ、LMAから大型ミリ波サブミリ波干渉計（LMSA）構想へ発展	
1988				
1990				
1991				
1992		1992.01 宇宙電波シンポジウム「LMA計画」（1992年1月8日～10日、福岡市仙石原文化センター）	1992.01 チリでの建設地調査開始	
1993				
1994	1994.06 日本学術会議議決案「21世紀に向けた天文学長期計画」	1994.09 宇宙電波シンポジウム「LMSA計画」の推進	日米での協力協議の開始	
1995				
1996				
1997			1997.03 日米共同ワークショップ「0.01秒角分解能によるミリ波サブミリ波天文学」で、LMA/MMA統合計画の策定	
1998		1998.02 宇宙電波シンポジウム「21世紀の大型観測装置による天文学」（1998年2月4日～5日、東京大学（本部））	1998.10 MMAの設計開発研究開始	1998.12 コンソ
1999			1999.06 米欧連でのアルマ望遠鏡構想	
2000			1999.10 アルマ望遠鏡ワシントンサイエンスシンポジウム、アルマ科学諮問委員会結成	
2001	2001.12 宇宙電波シンポジウム「21世紀の電波天文学」（2001年12月5日～6日、国立天文台（三鷹））	2001.04 アルマ望遠鏡 日米欧3者共同建設の決議書の締結		2001.11 アルマ望遠鏡建設予算の決定
2002	2002.12.11 日本学術会議 第5部会議員型 ALMA 計画に関する検討会議	2002.04 アルマ望遠鏡試作アンテナ予算の決定		2002.04 アルマ望遠鏡建設予算の決定
2003		2003.09 宇宙電波シンポジウム「ALMA 時代のサイエンスと研究推進体制」（2003年9月9日～11日、国立天文台（三鷹））	2003.02 米欧によるアルマ望遠鏡（Atacama Large Millimeter/submillimeter Array）2003.11 総工式を開始	
2004			2004.04 アルマ望遠鏡建設予算の決定	
			2004.09 日本が関わったアルマ望遠鏡の共同建設開始。正式名称が Atacama Large Millimeter/submillimeter Array に。	

計画立案に約20年を費やした



## プロジェクトの概要

## 観測運用の開始と三者協定

- 2011(H23)年：日米欧のアンテナ16台で初期科学観測開始
- 2012(H24)年：初期科学観測における科学的成果を発表
- 2013(H25)年：本格運用を開始してチリ現地で開所式を
- 2015(H27)年：日米欧でアルマ望遠鏡の運用に関する三書に署名した。これによって、三者によるアルマ望遠鏡の協力運用を今後30年+αにわたって継続する枠組みが確定



開所式における福井照文部科学副大臣（当時）の祝辞



東京で開催した三者協定署名

11



## アルマ望遠鏡の沿革—建設期



### 科学技術・学術審議会

特定研究領域推進分科会 我が国における天文学研究の推進について  
学術分科会 アルマ実施計画に関する評価について

2000

2002

総合科学技術会議（CSTP）

2003

2003.09.17 総合科学技術会議 専門調査会 評価専門調査会「アルマ計画」評価検討会（事前評価）第1回  
2003.10.06 総合科学技術会議 専門調査会 評価専門調査会「アルマ計画」評価検討会（事前評価）第2回

2004

2005

"総合科学技術会議 専門調査会 評価専門調査会 大規模新規研究開発の評価のフォローアップ※評価専門調査会第45回（2005.05.19）、第46回（2005.06.01）、第47回（2005.07.07）、第48回（2005.08.04）の4回に渡ってフォローアップを実施"

### 2006 独法化

2007

総合科学技術会議 平成20年度概算要求における科学・技術関係施策の優先度判定結果「アルマ計画の推進」

2008

総合科学技術会議 平成21年度概算要求における科学・技術関係施策の優先度判定結果「アルマ計画の推進」

2009

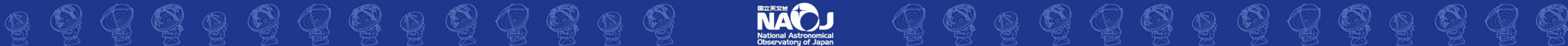
総合科学技術会議 平成22年度概算要求における科学・技術関係施策の優先度判定結果「アルマ計画の推進」

2010

総合科学技術会議 平成23年度概算要求における科学・技術関係施策の優先度判定結果「アルマ計画の推進」

"ALMA Construction and Operations" (invited talk by Iguchi-san at the Gopira symposium 2021)

<http://gopira.jp/sym2021/program.html>



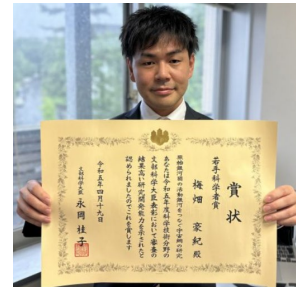
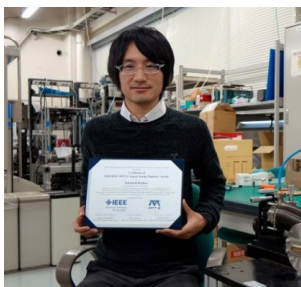


# Accumulating achievements

(modified from the original slide)

High growth rate of papers from ALMA,  
comparable to HST and VLT

Cultivating the community: researchers and  
developers/engineers



Credit: NAOJ 18







# Process in Japan to start ALMA2

- January 2020: Selected as one of the high priority projects in the **Master Plan 2020** by the Science Council of Japan
  - **Academic significance**, consensus of the research community, clarify of implementation entity, feasibility, open-user system, value for society, level of maturity, strategic nature/urgency
  - **計画の学術的意義**、科学者コミュニティの合意、計画の実施主体の明確性、計画の妥当性、共同利用体制の充実度、社会的価値、成熟度、我が国としての戦略性・緊急性
- September 2020: Selected in the MEXT **Roadmap 2020**

Academic significance, consensus of the research community, implementation entity, open-user system, feasibility, urgency, strategic nature, support from society and the public  
計画の学術的意義、研究者コミュニティの合意、計画の実施主体、共同利用体制、計画の妥当性、緊急性、戦略性、社会や国民からの支持
- April 2022: **Transition** evaluation for ALMA in the MEXT Frontier Project
  - Mainly achievements of project
- June 2022: **Pre-evaluation** for ALMA2 in the MEXT Frontier Project
  - Academic significance, consensus of the research community, implementation entity, open-user system, feasibility, urgency, strategic nature, support from society and the public, response to the previous action items





# Overall comment in the evaluation report

This project aims to further improve the performance of ALMA, which has the world's highest sensitivity and resolution as a radio telescope, in order to conduct deeper exploration of planetary formation and evolution, material exploration, and the history of galaxies and other bodies. The project is **highly urgent and strategic**, and will be supported by the domestic and international research community as well as by society and the public. In order to achieve the three scientific goals based on the excellent results to date, Japan will continue to make progress in **improving the telescope's performance** (doubling its resolution, sensitivity, and frequency bandwidth) and maintaining it properly, **including measures to prevent it from aging**. Japan will continue to lead cutting-edge radio astronomy research in strong cooperation with the U.S. and Europe, and maintain its international competitiveness. Considering the above, we evaluate that **this project should be actively pursued and that it should be started as soon as possible**.

本計画は、電波望遠鏡として世界最高の感度、解像度を有するアルマ望遠鏡の性能をさらに向上させることで、  
 現行計画において目標とした惑星形成・進化の検証、物質探査、銀河と諸天体の歴史の解明について、より深い  
 探索を行うことを目指すものであり、**高い緊急性、戦略性を持ち、国内外の研究者コミュニティの合意や社  
 会・国民の支持を得られる計画として評価できる**。これまでの優れた成果をベースとした3つの科学目標を達  
 成するため、**望遠鏡の性能向上（解像度、感度、周波数帯域を2倍とする）と老朽化対策を含めた維持管理を  
 適切に進めることにより、引き続き我が国が米欧と強力に連携して最先端の電波天文学研究を牽引し、国際競  
 争力を維持していくことが期待される**。以上を総合的に勘案し、**本計画は積極的に進めるべきであり、早急に  
 着手すべきである**と評価する。

（文部科学省 科学技術・学術審議会 学術分科会 研究環境基盤部会 学術研究の大型プロジェクトに関する作業部会による  
 大規模学術フロンティア促進事業の「事前評価」報告書より抜粋 [https://www.mext.go.jp/content/20220728-mxt\\_gakkikan-000025951\\_1.pdf](https://www.mext.go.jp/content/20220728-mxt_gakkikan-000025951_1.pdf)）







# Building and operating large-scale facilities

A few comments based on my personal observations and those through conversations with people.

- No projects are the same. The nature of each project is different, as is the external environment surrounding each project at any given time.
  - It takes efforts, but just because we work hard doesn't mean it will happen.
- A project should bring growth for the community and the institution implementing the project.
  - Research activity level, number of people and positions
  - Accumulation of experiences and skills in NAOJ, in-kind contribution as much as possible
- The importance of science is widely understood. In addition to this, it is necessary to appropriately demonstrate the contribution to the society.
  - The criteria for review includes various aspects, not reviewed solely based on scientific significance.
- Clear (and quantitative) goal setting is requested.

