NAOJ future symposium 2021

Planetary system formation

What are the major issues in the science, and what approaches can be considered?

- This talk does not cover the chemical properties of disk material (evolution of gas and dust compositions, snowlines, water) .
- Biased to observations. Theorists, please add comments.
- There should be some bias. Observers, please add comments.

Misato Fukagawa
NAOJ, East Asia ALMA Regional Center

国立天文台 NAOJ National Astronomical Observatory of Japan

Credit: NASA/FUSE/Lynette Cook, ESO/C.Malin

Long-standing, central question

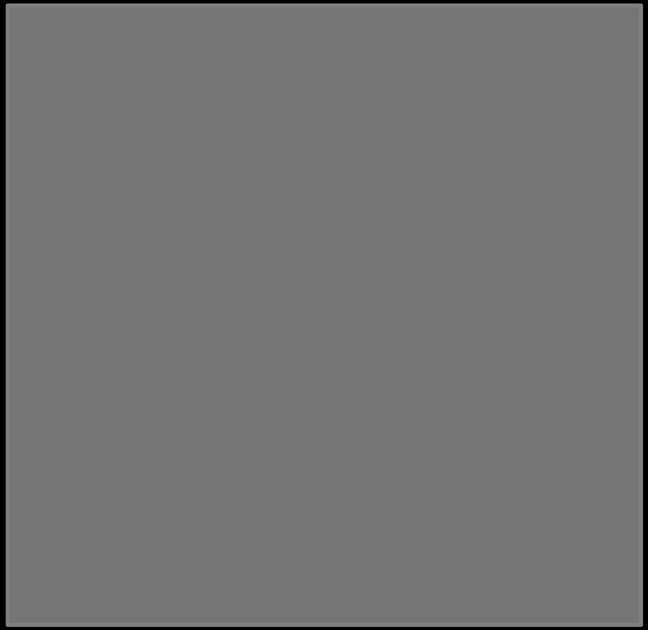
How do planetary systems form and evolve?

What brings about the diversity of planets and planetary systems?

What is the critical factor in forming our Earth and Solar System?

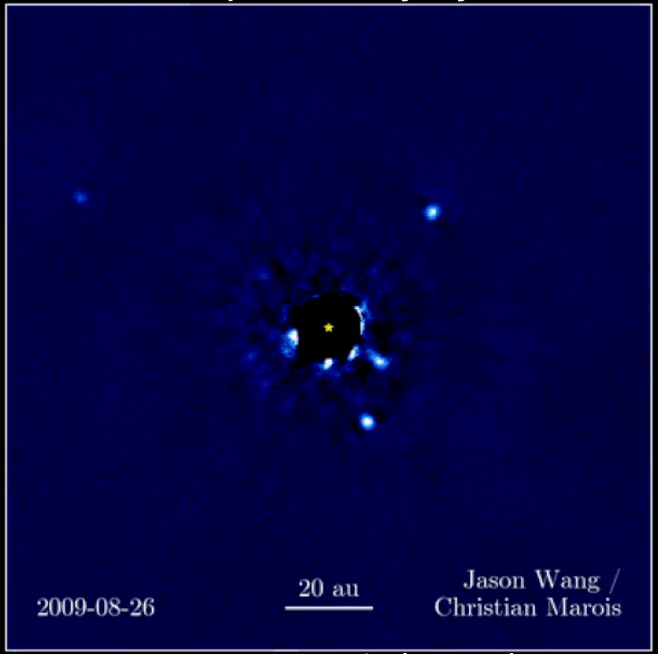
…

Protoplanetary disk with gas and dust



ALMA Partnership et al. (2015)

Matured planetary systems



Marois et al. (2008) etc.

…

Initial condition of planet formation and evolution = Protoplanetary disks are complicated, really.

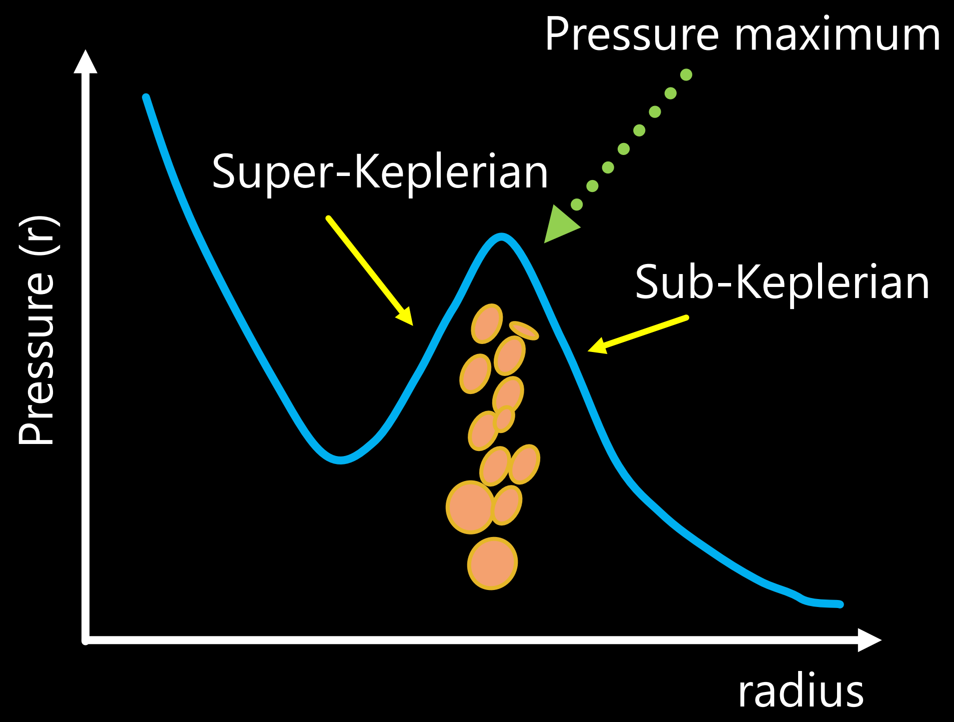
Density, temperature, abundance are the function of r, z, Φ, and time

Henning & Semenov (2013)

- Radial inward drift due to the gas drag
- Dust coagulation, fragmentation, etc.

Gas is supported by pressure, and rotates around the central star with a different velocity from solids

Okuzumi (2014)



e.g., Klahr & Henning (1997), Pinilla et al. (2012)

Two major directions as always

Completing the census

[Zhang et al. (2018),](#)
[Lodato et al. (2019)](#)

[Andrews et al. (2018)](#)

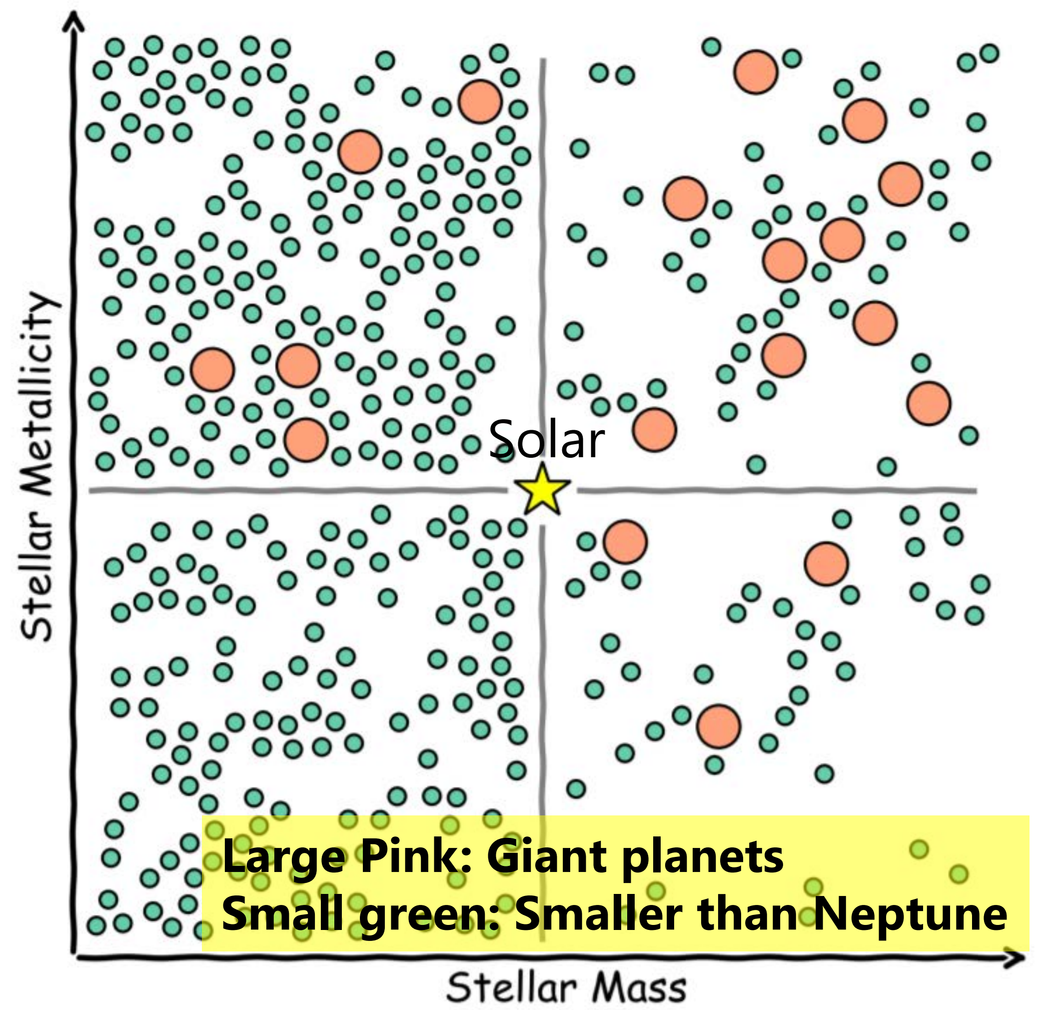
Understanding the mechanisms

- Spatial distribution of:
  - gas and dust density
  - Temperature
  - Magnetic fields, gas viscosity

What are known for planet populations

- Planets are more common towards lower masses or smaller sizes (e.g., Suzuki et al. 2016)
- Giant planets (more massive than Neptune) orbit 10-20% of stars (e.g., Fernandes et al. 2019), occurrence rate peaks at 2—3 au
- Hot Jupiters are rare (<1 %) (e.g., Cumming et al. 2008)
- Occurrence of giant planets are positively correlated with the stellar mass (e.g., Johnson et al. 2010)
- Sub-Neptunes are more common around low-mass stars (e.g., Mulders 2015)
- Giant planet occurrence rate shows a correlation with the stellar metallicity (e.g., Fischer & Valenti 2005)

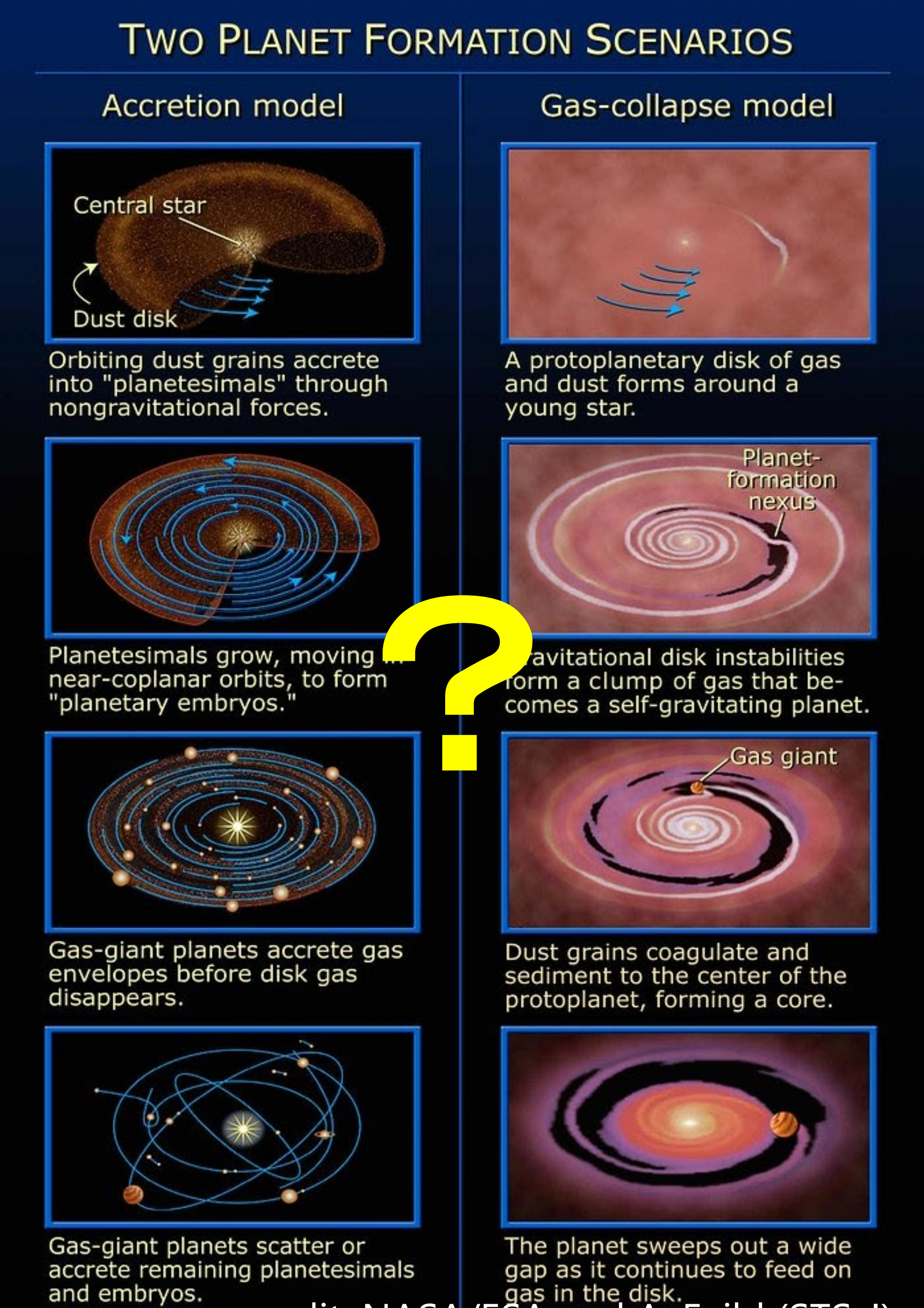
Occurrence rate (density of symbols)



Mulders (2018)

Giant planet formation

- Core accretion model – planets are formed through "bottom up" process, producing ~10 Earth-mass solid core followed by the gas accretion within the lifetime of gas (~3 million years)
  - High surface density of solids is necessary (e.g., Ikoma et al. 2000)
  - Consistent with the correlation between the stellar metallicity and giant planet occurrence, but cannot explain the whole process including the efficient growth from dust grains to km-sized bodies theoretically
- Disk gravitational instability – planets are formed in massive and cold protoplanetary disk
  - Inconsistent with the correlation between the stellar metallicity and giant planet occurrence (measured at short periods), but can explain the presence of some detected wide-orbit planets

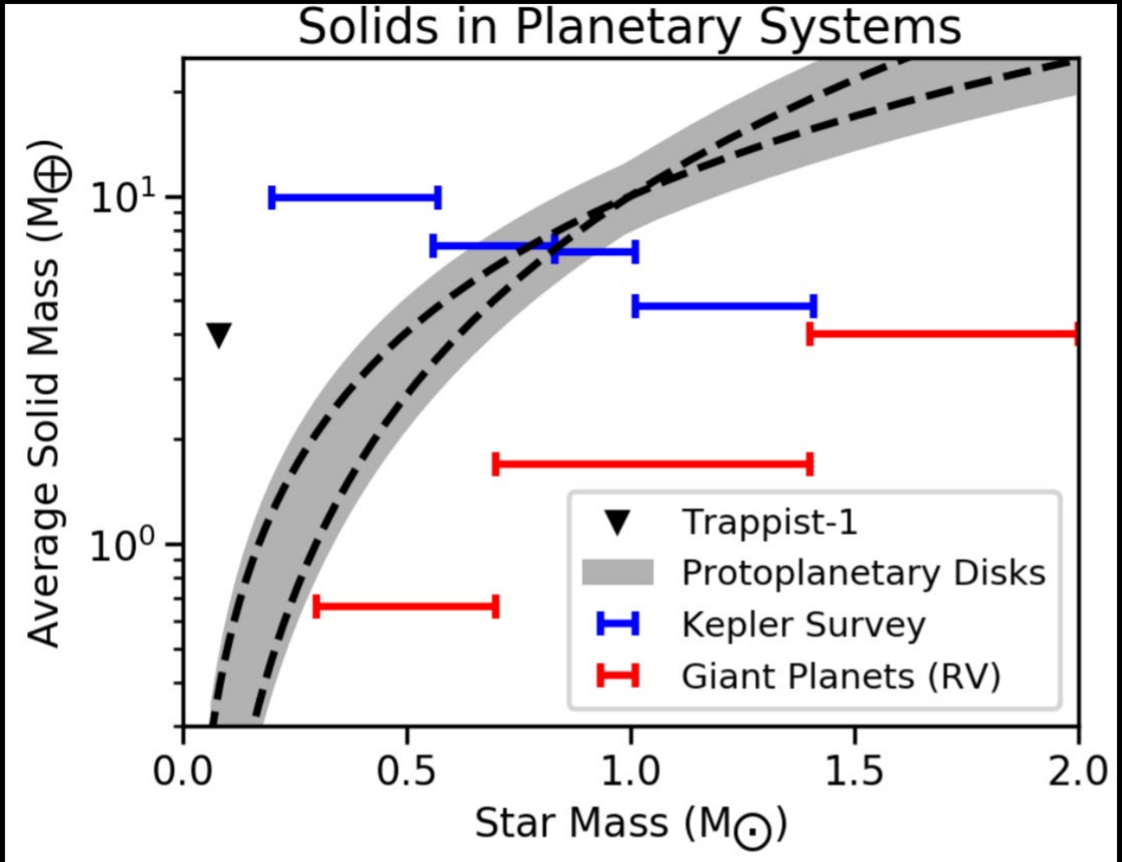


Review by Mulders (2018)

credit: NASA/ESA and A. Feild (STScI)

Formation of Neptune-mass planets

- In situ formation
  - Local surface density matters. (e.g., Kokubo & Ida 2002)
  - Challenge: It is not clear if the inner regions of protoplanetary disks can contain enough mass that grow into planetary embryos (Schlichting 2014)
- Planet migration
  - Inward migration with the disk gas
  - Challenge: t is not clear how an enhancement of the inner disk density by drift of solids that precedes the giant impact phase would impact the planet population.



Blue: <150 days planets with Kepler
Red: RV planets, assuming 20 M_E solid per planet

Review by Mulders (2018)

Completing the census

Linking matured exoplanets and protoplanetary disks

Planets around main-sequence (or older) stars

Migration?

Putative planets just formed in disks

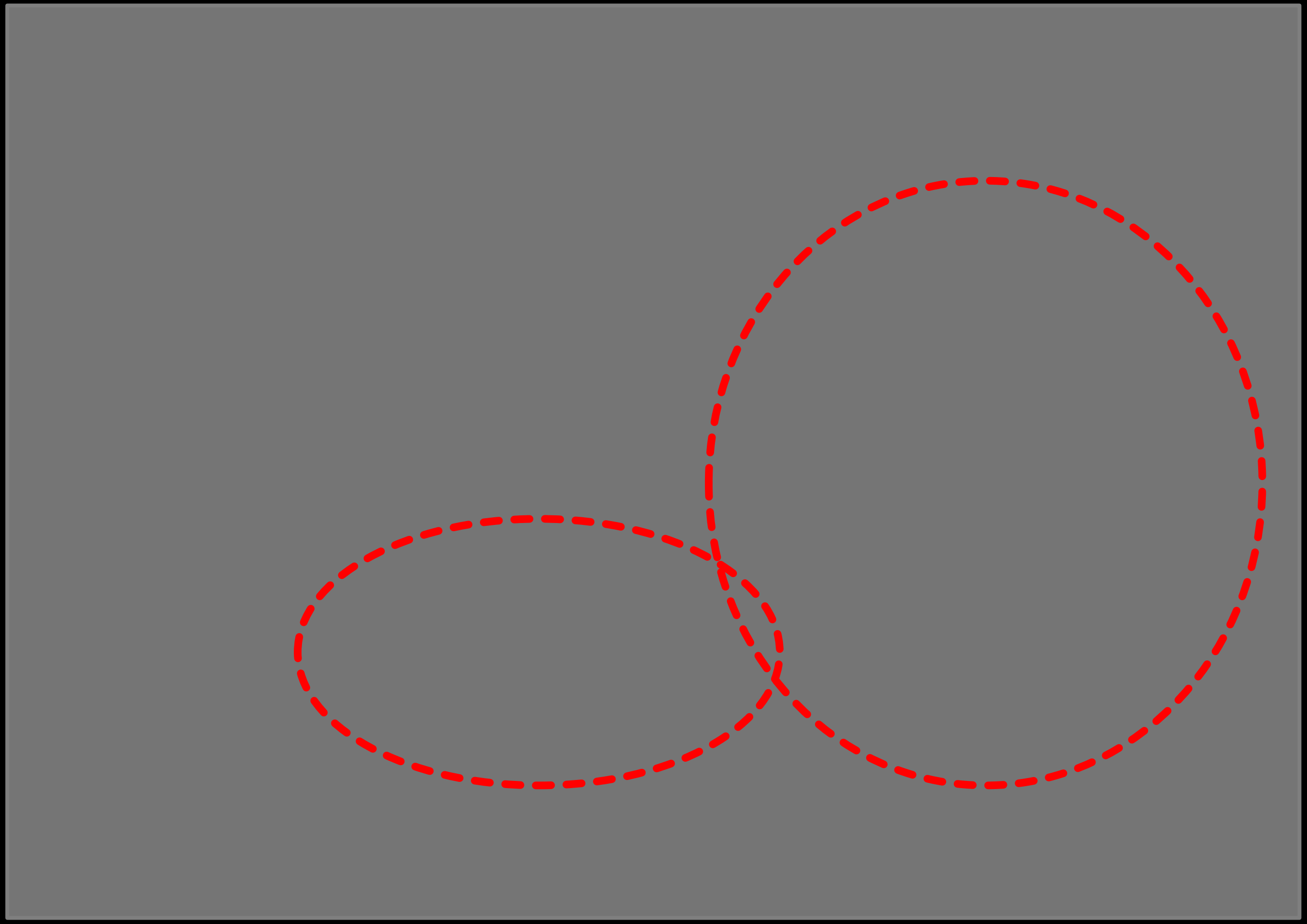
- Dust density gaps are detected at >~10 au
- Plausible cause is planets opening the gaps

Attempts have started, but still very challenging

Zhang et al. (2018), Lodato et al. (2019), Andrews et al. (2018)

Completing the census

Linking matured exoplanets and protoplanetary disks



Zhang et al. (2018)

Exoplanets: need to fill the regions that cannot be probed with the current generation instruments

- Are Solar-system like ones rare?
- How does it depend on the properties of the central stars?

Completing the census of exoplanets, including systems like our own Solar system

Microlensing to cover 1—10 au regions, Measurements to detect earth-mass planets, to widen the parameter space for the central star properties

Completing the census

Linking matured exoplanets and protoplanetary disks

Towards 1-au:
Next-generation
mm-cm
interferometer

Towards the
complete census:
Future exoplanets
surveys

Disks: Need to fill the regions in <10 au

- What are the distributions of solids and gas in the terrestrial planet forming regions?
- What are the structures of compact disks?

Probing the inner (<10 au) regions of protoplanetary disks

1-au resolution in submm/mm for optically thin disks
1-au resolution at longer wavelength for optically thick disks in submm/mm

Zhang et al. (2018)

Completing the census

Disk demographics

- Substructures are ubiquitous <u>in large disks</u> with the ages of million-years of ages, and possibly for younger stages, with some diversity.
- Current hypothesis
  - Giant planets open those gaps. (Kanagawa et al. 2015)
  - There are other hypothesis for ring formation. (e.g., Okuzumi et al. 2016, Takahashi & Inutsuka 2016)

Structured disks can keep
the large mass for a long-time.
Dust trapping by pressure bumps by GPs?

van der Marel et al. (2021)

Resolution ~5 au, Andrews et al. (2018)

Completing the census

Disk demographics

- The majority can be smooth compact disks.
  - Losing the outer region by the radial drift? Born with small disks?
- Some of the compact disks are optically thick at mm wavelengths.

Resolution ~16 au, Long et al. (2019)

Revealing structures in the compact disks

1-au resolution in submm/mm for optically thin disks
1-au resolution at longer wavelength for optically thick disks

Completing the census

Disk demographics

Scenario on the giant planet formation is being revealed in the outer regions?

van der Marel & Mulders (2021)

Disk observations

Roughly consistent

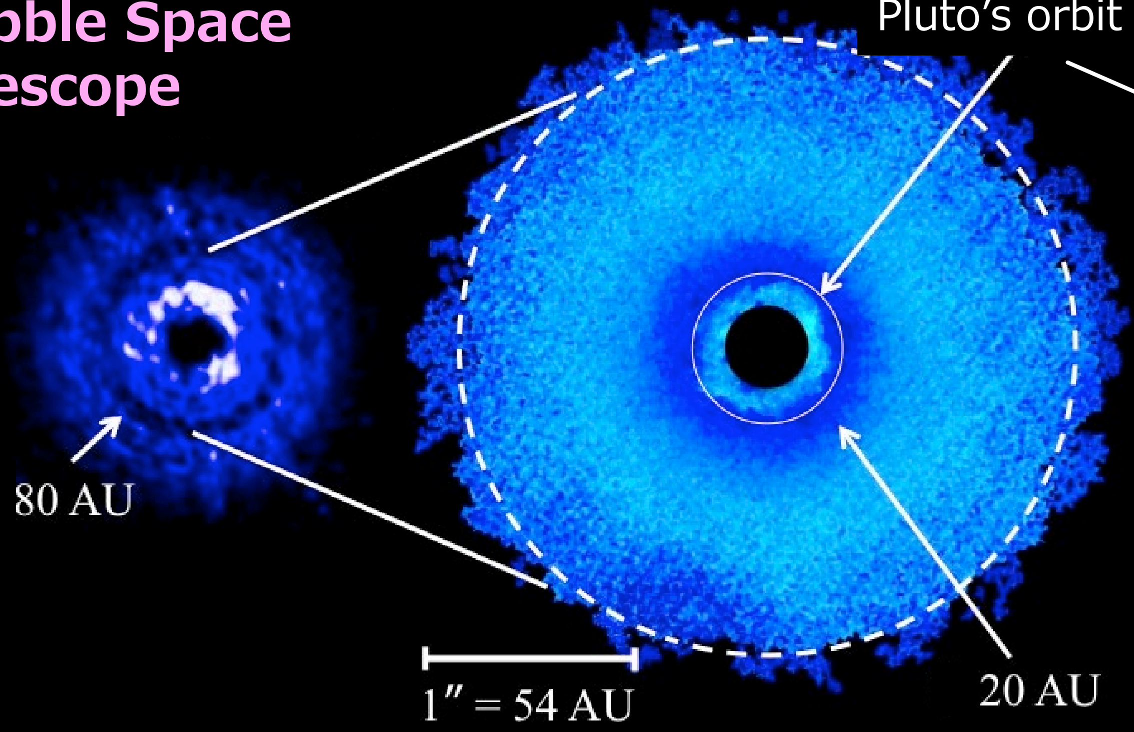
Prediction of disk structures from exoplanet detections

Completing the census

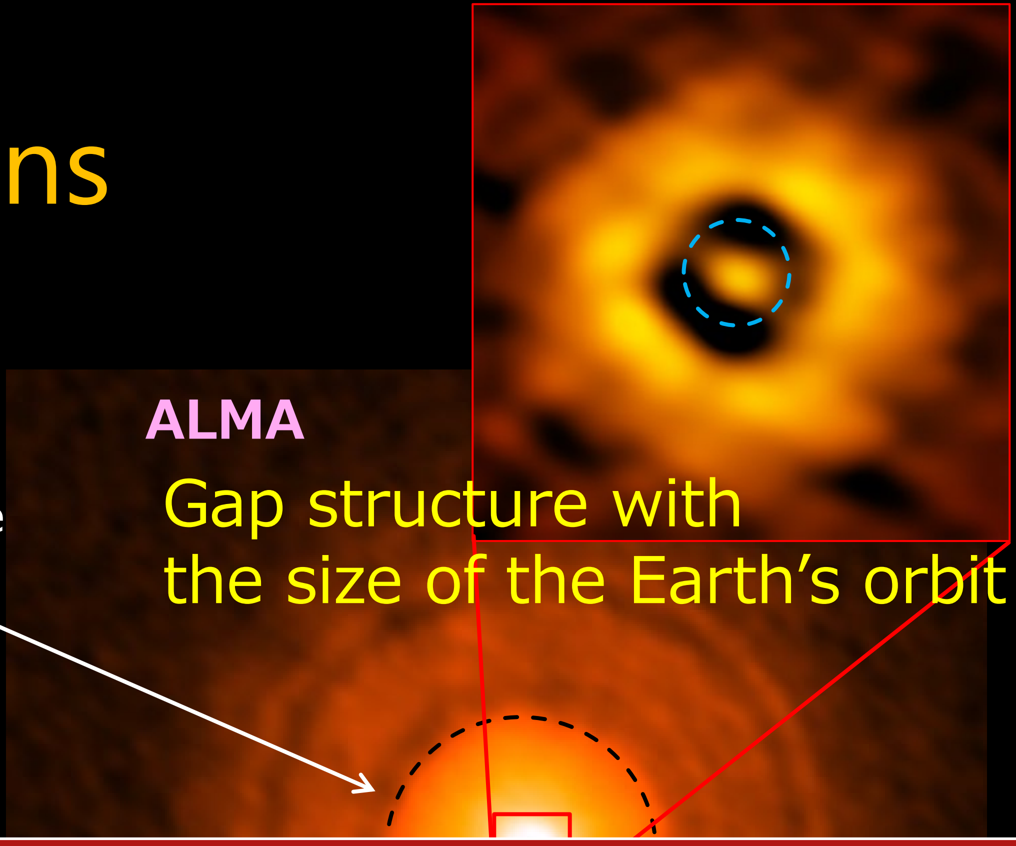
Towards 1-au regions

Hubble Space Telescope

Subaru



ALMA



"TW Hya"
Uniquely nearby young star

1 au resolution for hundreds of disks, to probe inner regions

1-au resolution in submm/mm for optically thin disks
1-au resolution at longer wavelength for optically thick disks

e.g., Andrews et al. (2016), Tsukagoshi et al. (2016), credit: NAOJ, ALMA

Understanding the mechanisms

Growth of solids

Small-scale enhancement, ~0.03 Earth-mass

Tsukagoshi et al. (2019)

1 au resolution for hundreds of disks

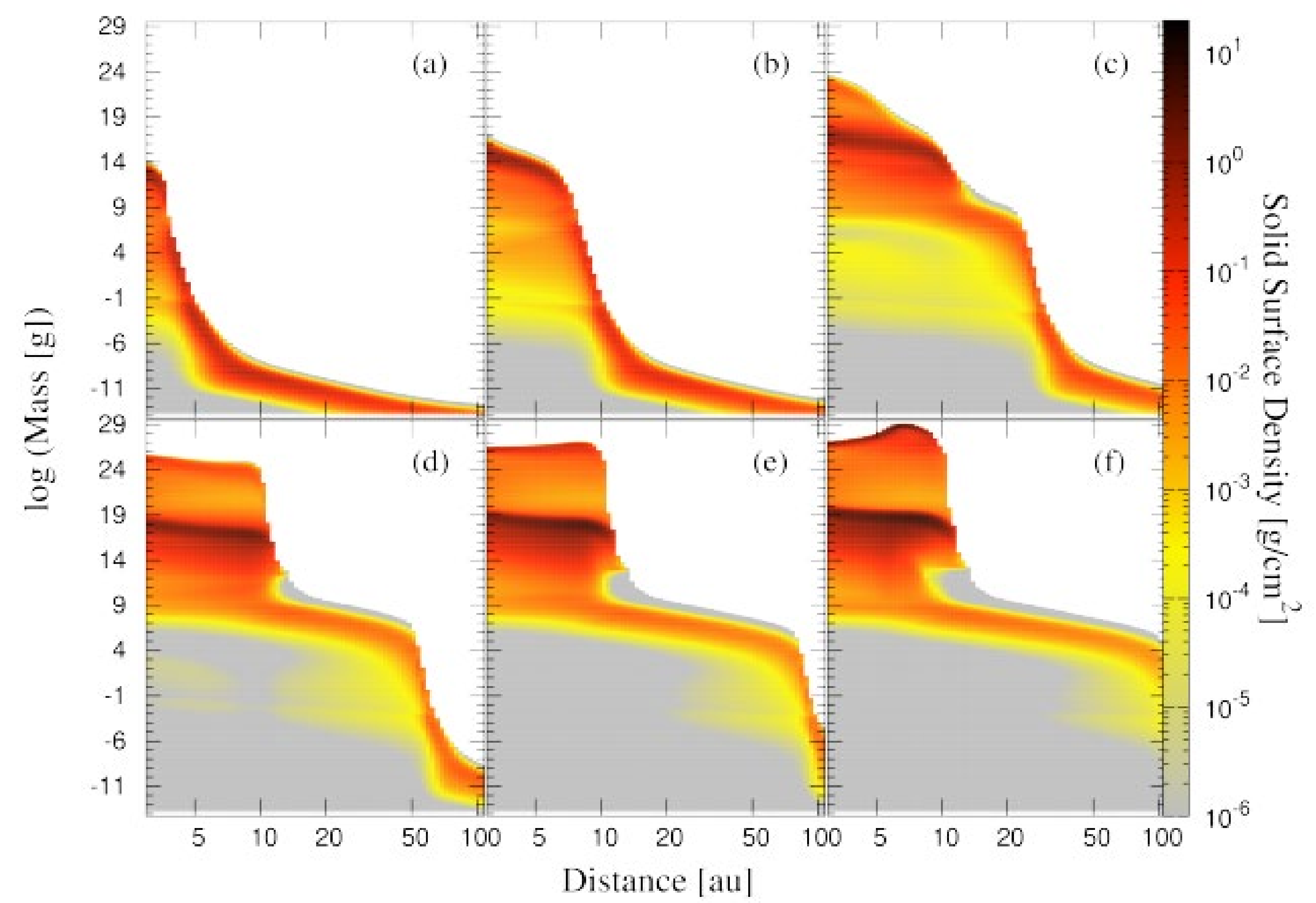
1-au resolution in submm/mm for optically thin disks or outer regions of all disks
1-au resolution at longer wavelength for optically thick disks

Growth of solids

Can we overcome the difficulty in core accretion-based models?

Full treatment from dust to planetary cores in a whole disk region is important.

Rapid formation of massive cores can be reproduced (Kobayashi and Tanaka 2021).



Kobayashi and Tanaka (2021)

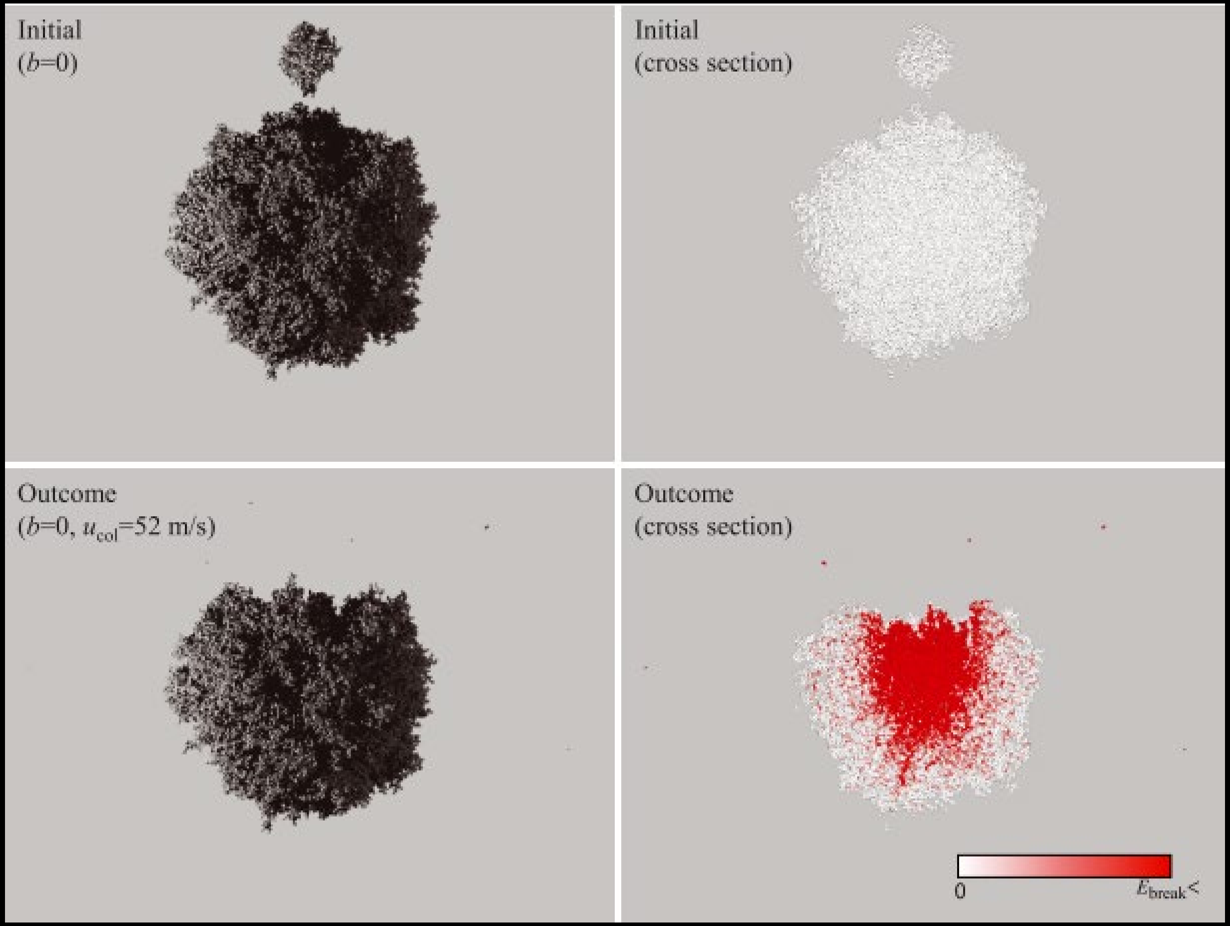
Understanding the mechanisms

Growth of solids

Growth efficiency needs to be investigated

- Particle sticking
- Most likely, dust grains are not compact spheres but in an aggregated form (e.g., Dominik & Tielens 1997)

Computational and experimental studies are important.



Wada et al. (2013)

Understanding the mechanisms

Growth of solids

- Grain size investigations in observations
  - Spectral index
  - Polarization (scattering) in optical, IR, and radio (e.g., Tazaki et al. 2017)
- Polarization data can be connected to the magnetic field

Polarization can be our advantage in science and technical development…?

Kataoka et al. (2015, 2017), Ohashi et al. (2019), Stephens et al. (2017)

Understanding the mechanisms

Gas mass

- Grain growth and dynamics of solids are controlled by the surrounding gas.
- At each age, how much gas is available? This relates to the timescale of making solid cores and formation of gas giant planets.

Bergin et al. (2013)

- Gas-to-dust mass ratio can be drastically different from the ISM.
- CO/H2 conversion is very uncertain.
- HD were detected for a very few (bright) disks so far.

Reliable measurements of H2 mass
Sensitive HD observations in far-infrared (ground state) at high spatial resolution

Understanding the mechanisms

Detailed gas kinematics

- Degree of turbulence, meridional flows, winds, accretion streams, spirals due to planets etc.
  - Spatial density structure, presence of gravitational perturbers, magnetic field (MRI) …

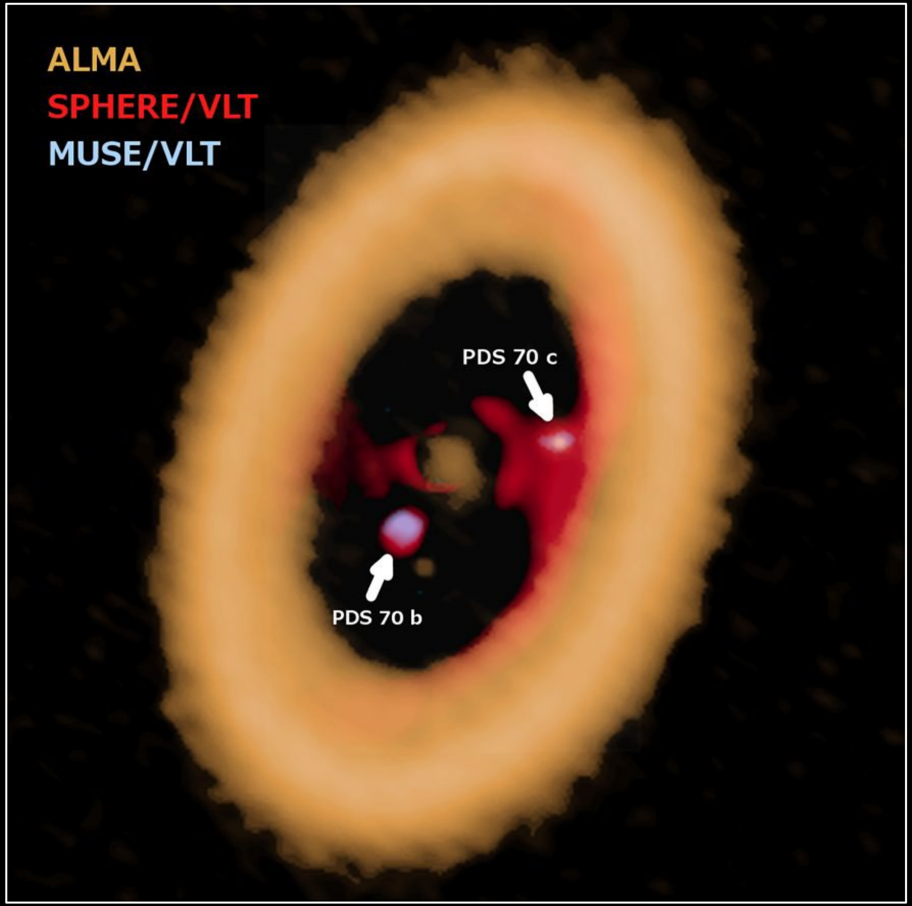
Teague et al. (2019)

Precise measurements of gas kinematics
High sensitivity for gas lines

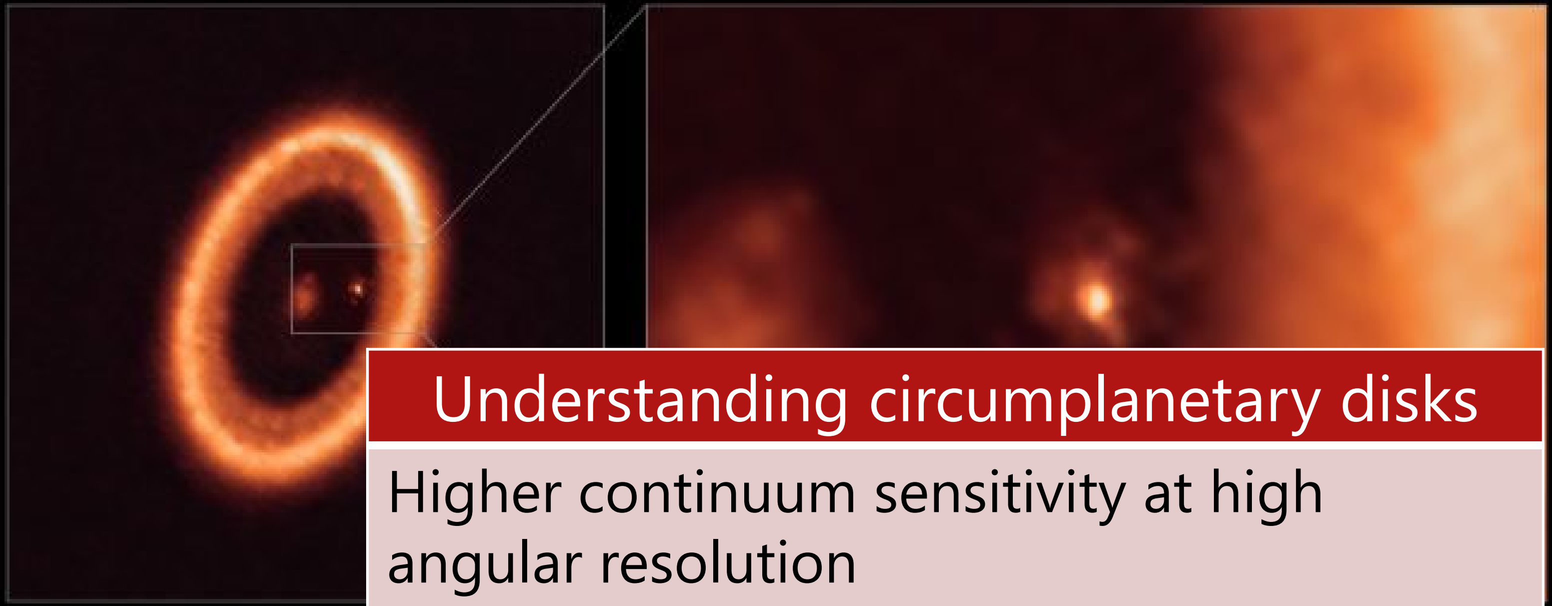
Understanding the mechanisms

Growing protoplanets, satellite formation

Not so easy yet although we have started to see them.



Credit: ALMA (ESO/NAOJ/NRAO) A. Isella; ESO., Isella et al. (2019)



Understanding circumplanetary disks

Higher continuum sensitivity at high angular resolution

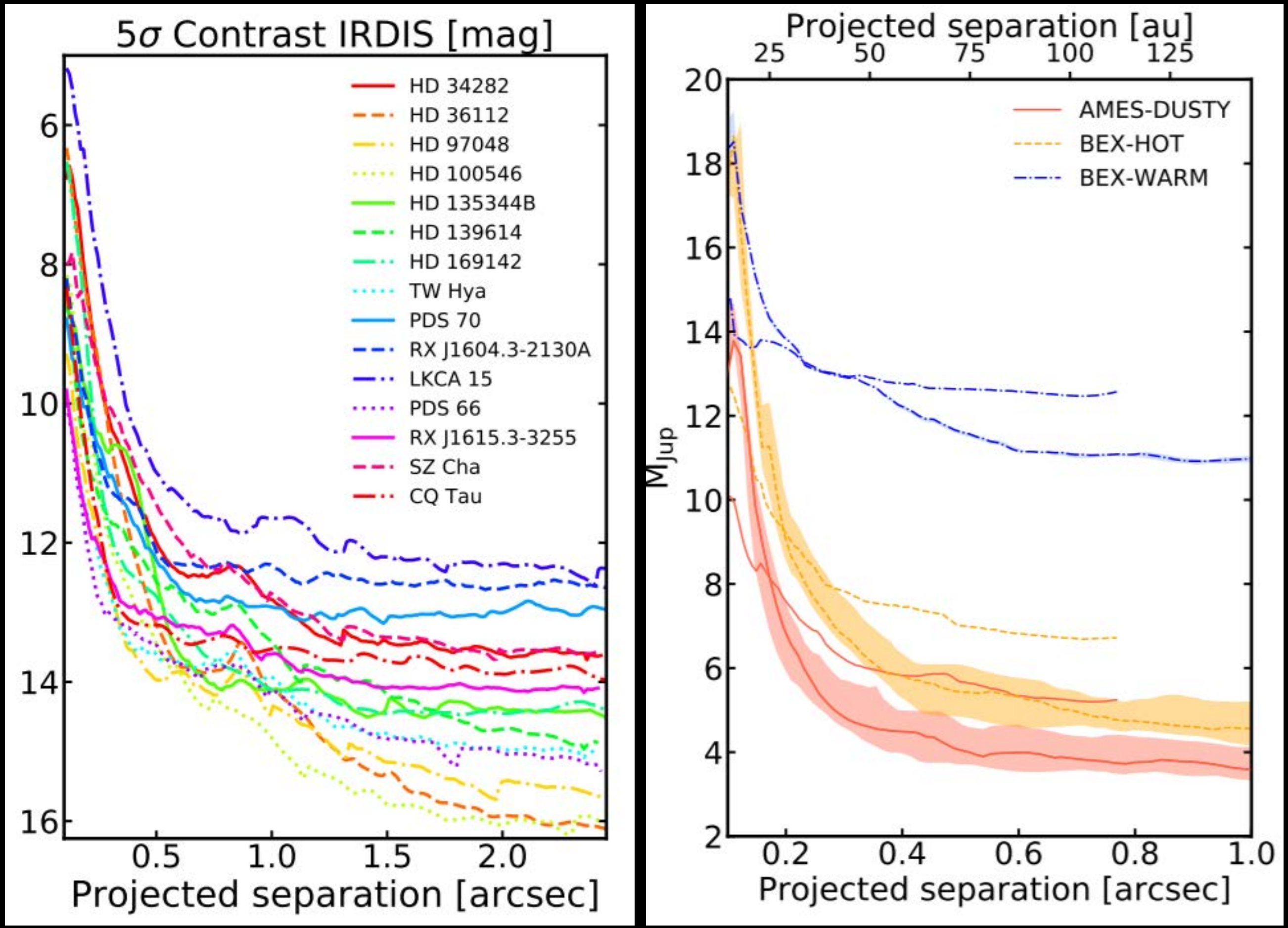
Optical/NIR spectroscopy with high contrast to detect gas accretion onto protoplanets

1.2 au in radius, ~0.031—0.007 Mearth (resolution~20 mas, 2.3 au)

Credit: ALMA (ESO/NAOJ/NRAO) Benisty et al.

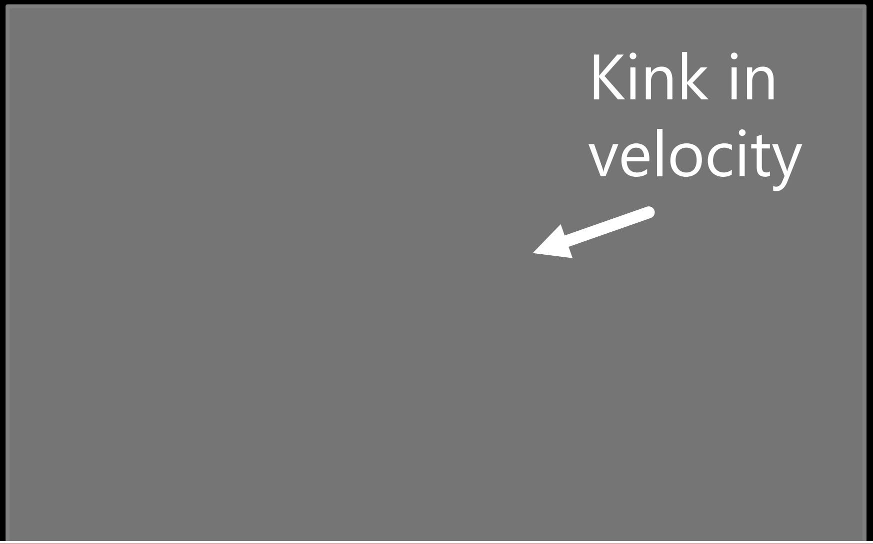
Growing protoplanets, satellite formation

Detection limit for planets in disks (still >3 Jupiter-mass)



Asensio-Torres et al. (2021)

New Tool?

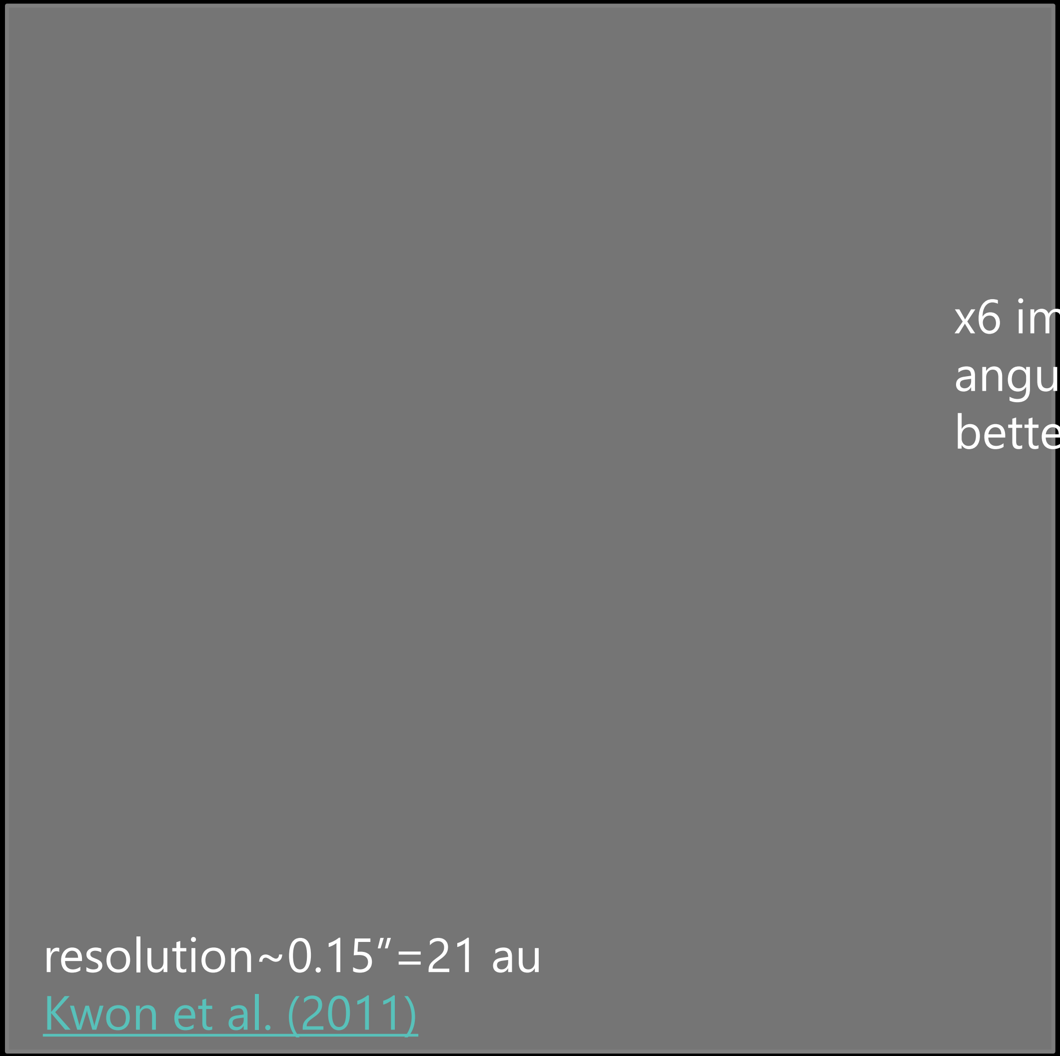


Detections of planets in disks

Higher contract optical/IR imaging
Higher sensitivity IR imaging
Sensitive line detections with high velocity resolution

Pinte et al. (2018)

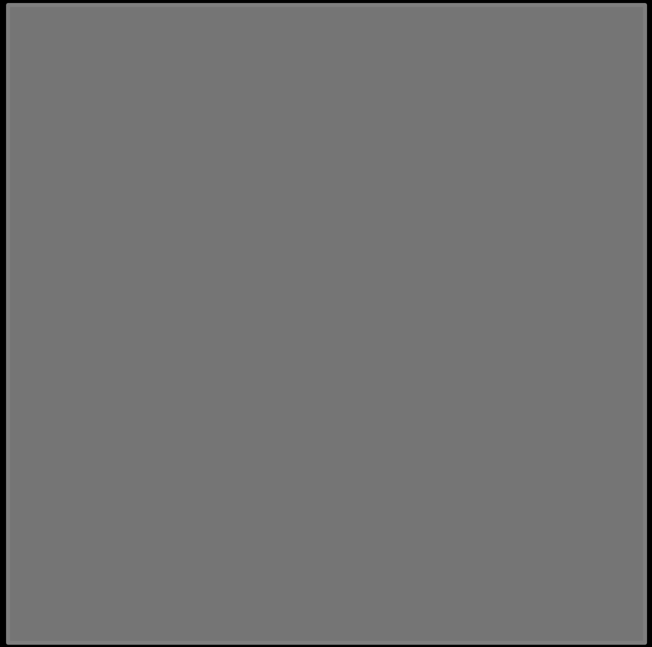
Expanding the age range: Younger stages



resolution~0.15″=21 au
Kwon et al. (2011)

x6 improvement in angular resolution, better image quality

Millimeter emission from dust grains in the disk of "HL Tau"



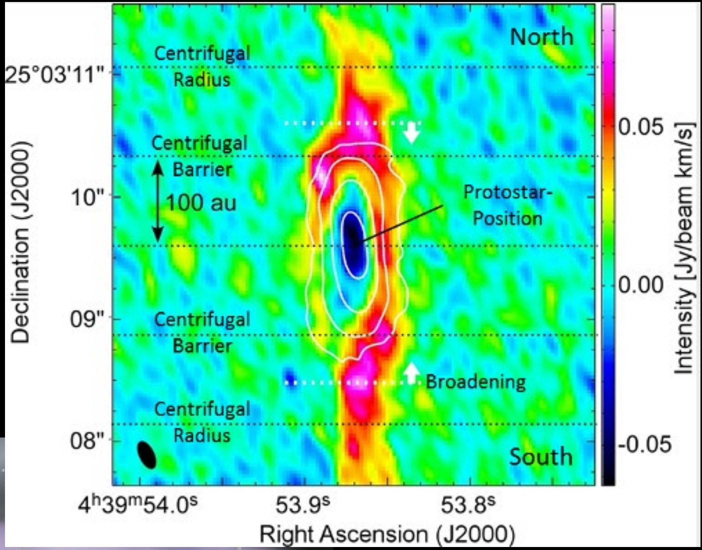
The 2014 ALMA Long Baseline Campaign: baseline up to 15.2 km, resolution ~25 mas (3.5 au) (ALMA Partnership et al. 2015)

Expanding the age range: Younger stages

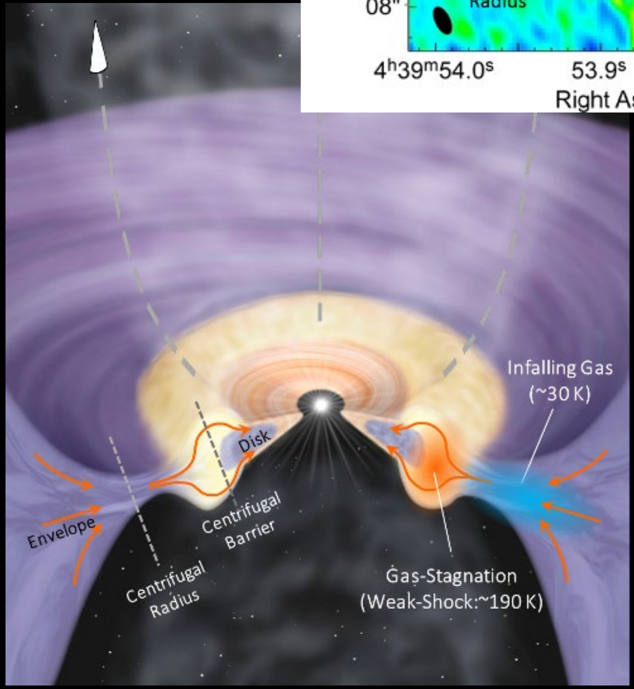
Planet forming process may already start in the protostellar phase (<1 million years).

- High angular resolution study has started, including the on-going ALMA Large Program by the Japanese PI
- Younger disks are more optically thick

Getting density structure in protostellar disks
Imaging at longer wavelengths (cm)



Sakai et al. (2014)

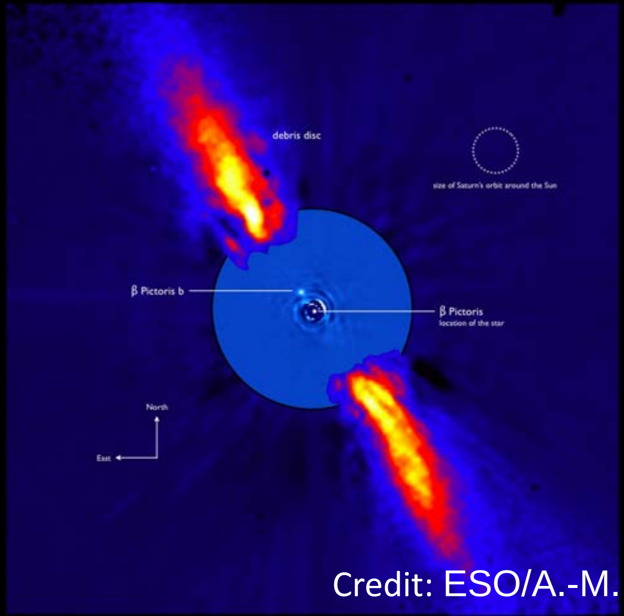


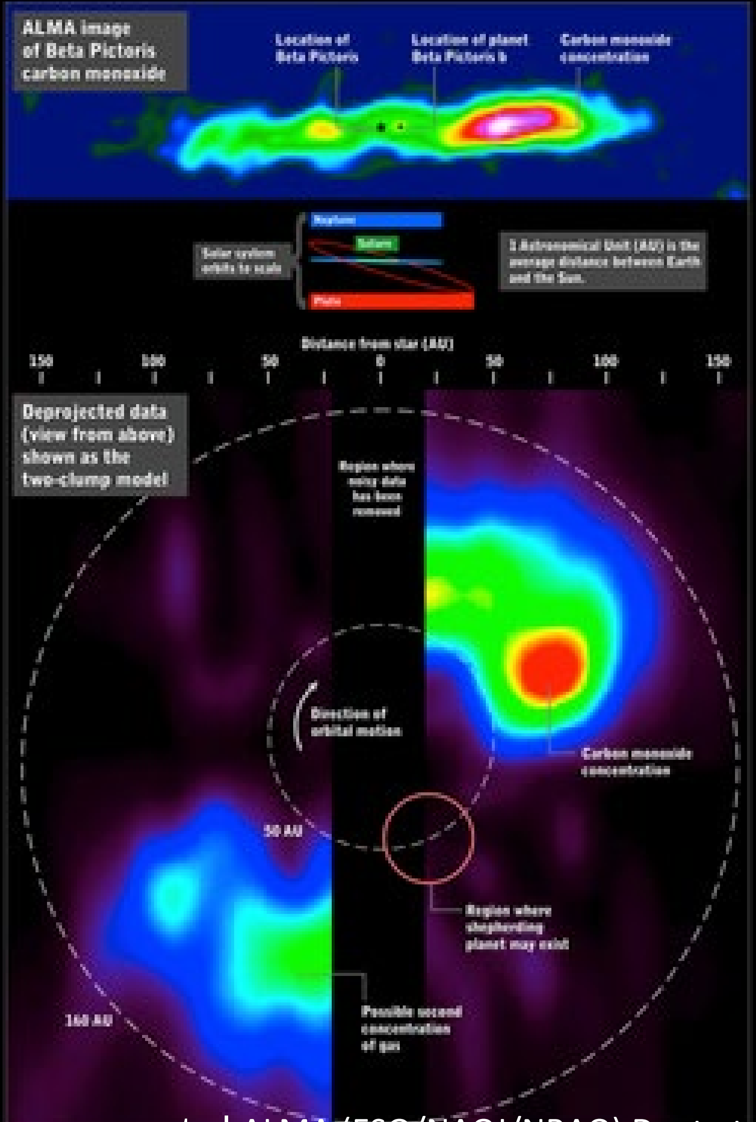
Credit: RIKEN, Sakai et al.

Expanding the age range: More evolved stages

- Debris disks around main-sequence stars
  - Gas dispersal process
  - 2nd generation, cometary gas
  - They should reflect the history of the planetary-system evolution to some extent

Detections of leftover or 2nd generation gas
High sensitivity in gas lines in submm/mm





Credit: ESO/A.-M. Lagrange et al.ALMA (ESO/NAOJ/NRAO) Dent et al.

What we want to obtain?	Which capability we want?
Completing the census of exoplanets, including systems like our own Solar system	Microlensing to cover 1—10 au regions, Measurements to detect earth-mass planets, to widen the parameter space for the central star properties
Probing the inner (<10 au) regions of protoplanetary disks Revealing structures in the compact disks 1 au resolution for hundreds of disks, to probe inner regions and wider radii	**1-au resolution** in submm/mm for optically thin disks or outer regions of all disks 1-au resolution **at longer wavelength** for optically thick disks in submm/mm
Reliable measurements of H2 mass	**Sensitive HD observations in far-infrared** (ground state) at high spatial resolution
Precise measurements of gas kinematics	**High sensitivity for gas lines**
Understanding circumplanetary disks	**Higher continuum sensitivity** at high angular resolution Optical/NIR spectroscopy with **high contrast** to detect gas accretion onto protoplanets
Detections of planets in disks	**Higher contract** optical/IR imaging **Sensitive line detections** with high velocity resolution
Getting density structure in protostellar disks	Imaging **at longer wavelengths (cm)**
Detections of leftover or 2nd generation gas	**High sensitivity in gas lines** in submm/mm

- A wide range of wavelengths can be used
  - Exoplanet detections: very wide range of wavelengths including UV and perhaps X-ray
  - Planets in disks: Optical, IR, and radio
  - Disk observations: IR and radio
  - Stellar properties: X-ray to radio
- Major stream for disk observations would be, higher angular resolution & higher line sensitivity, with higher contrast in opt/IR and longer wavelengths in radio (personal opinion)

Review by Andrews et al. (2020)

横軸 ◆星・惑星系形成・系外惑星

○ レビューアー：[天文学的アプローチ]、[惑星系形成]、[系外惑星]（バックアップ：）

コミュニティ	プロジェクト	（萌芽的テーマ）
V懇	JVN --超高分解能 (大質量形成時の爆発的質量降着が該当?)	将来：メートル波VLBIによる系外惑星研究？
宇電懇	ALMA2(大型国際) -- ミリ波サブミリ波帯：高分解能・高感度(on-going)	
	LST(大型国際) --ミリ波サブミリ波帯：広域・高感度	
	ngVLA(大型国際) --ミリ波センチ波帯(1.2-116GHz)：高分解能・高感度	
	SKA1(大型国際) --センチ波メートル波帯(0.1-25GHz)：高視野・高感度	
	ATT10(中型) --サブミリ波THz波帯：広域・高感度(南極)	
地球型惑星探査として		
光赤天連	すばる1(大型) --	
	TMT(大型)：すばる後継or連携？	
	MICHI (TMT用赤外線装置)：中間赤外での直接検出の観点	
	HAbEx：近傍での探査・ハビタビリティ	
	JASMINE :時間軸位置天文の観点	
	ExoJASMINE：近赤外、晩期型星まわりでの探査、褐色矮星気象	
	LAPYUTA: 系外惑星形成過程	
	PSI：M型星まわりでの探査、星周円盤観測(偏光含む)	
系外惑星一般の探査として		
光赤天連	LOTUS：近傍でのスノーライン以遠の惑星探査	
	188cm望遠鏡 & HIDES-Fと岡山可視天文コム：系外惑星サーベイ	
	せいめい望遠鏡：間接検出-直接検出	
	星形成プロジェクト：近赤外分光による統計研究、主系列星進化・年齢	
	Roman：系外惑星形成過程	
	MOA：系外惑星形成過程	
	PRIMEx：系外惑星形成過程	

Project list mixed for star and planet formation

Please see more details on the timeline for each project in Ikoma-san's slide

Planets (in habitable zones) around M dwarfs

Planets in wider orbits, lower mass planets

Subaru, OAO188, Seimei, JASMINE

Earth-like planets, and those around the Sun-like star

TMT, TMT/MICHI, TMT/PSI

Planetary systems like our own… or not (covering the same parameters space)

Roman, MOA, PRIMEx, LOTUS

Census of young planets in disks

TMT, TMT/PSI

1-au resolution, structure in a wide range of radii

Circumplanetary disks

Disks around more M dwarfs

ALMA

Density structure and initial planet-mass function down to 1-au regions

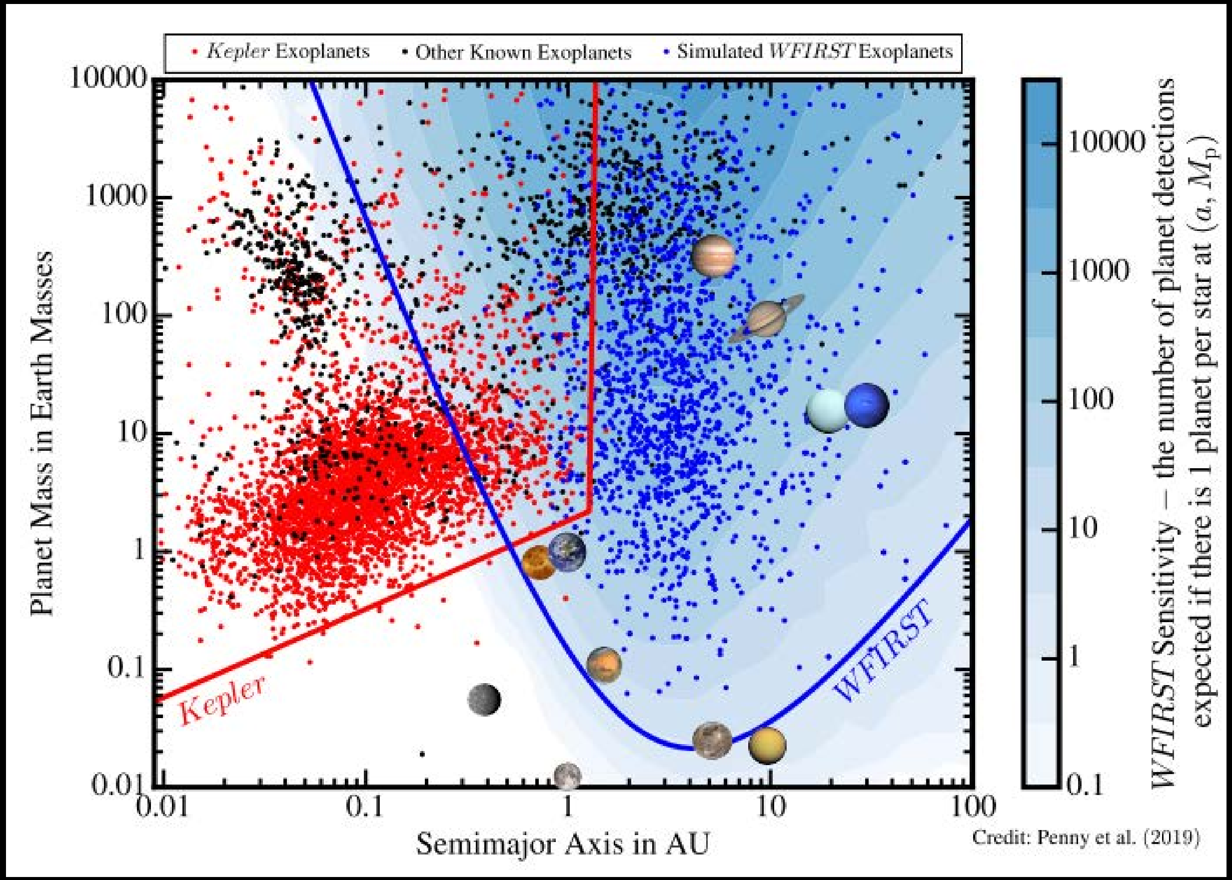
ngVLA

2030

2040

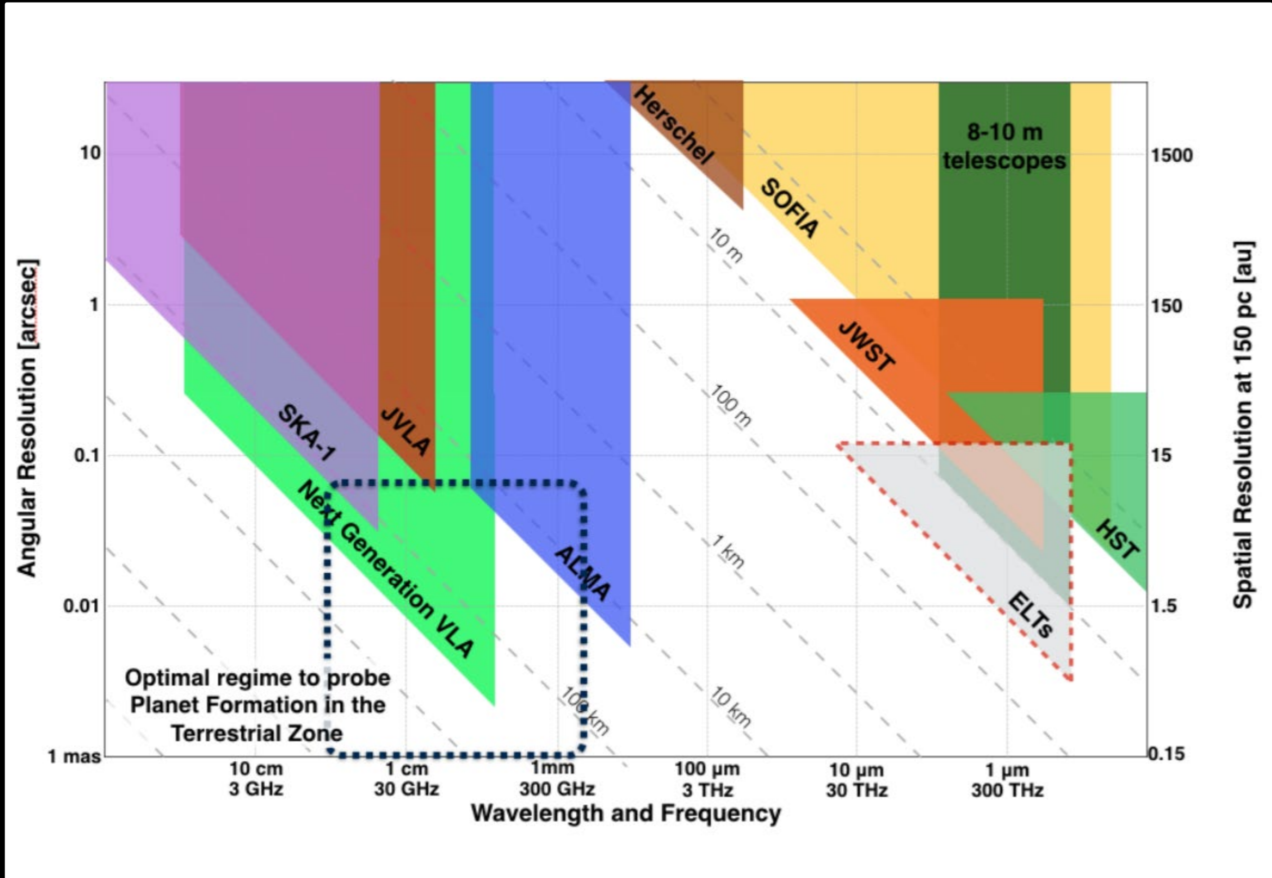
Examples

Roman



credit: Penny (2019)

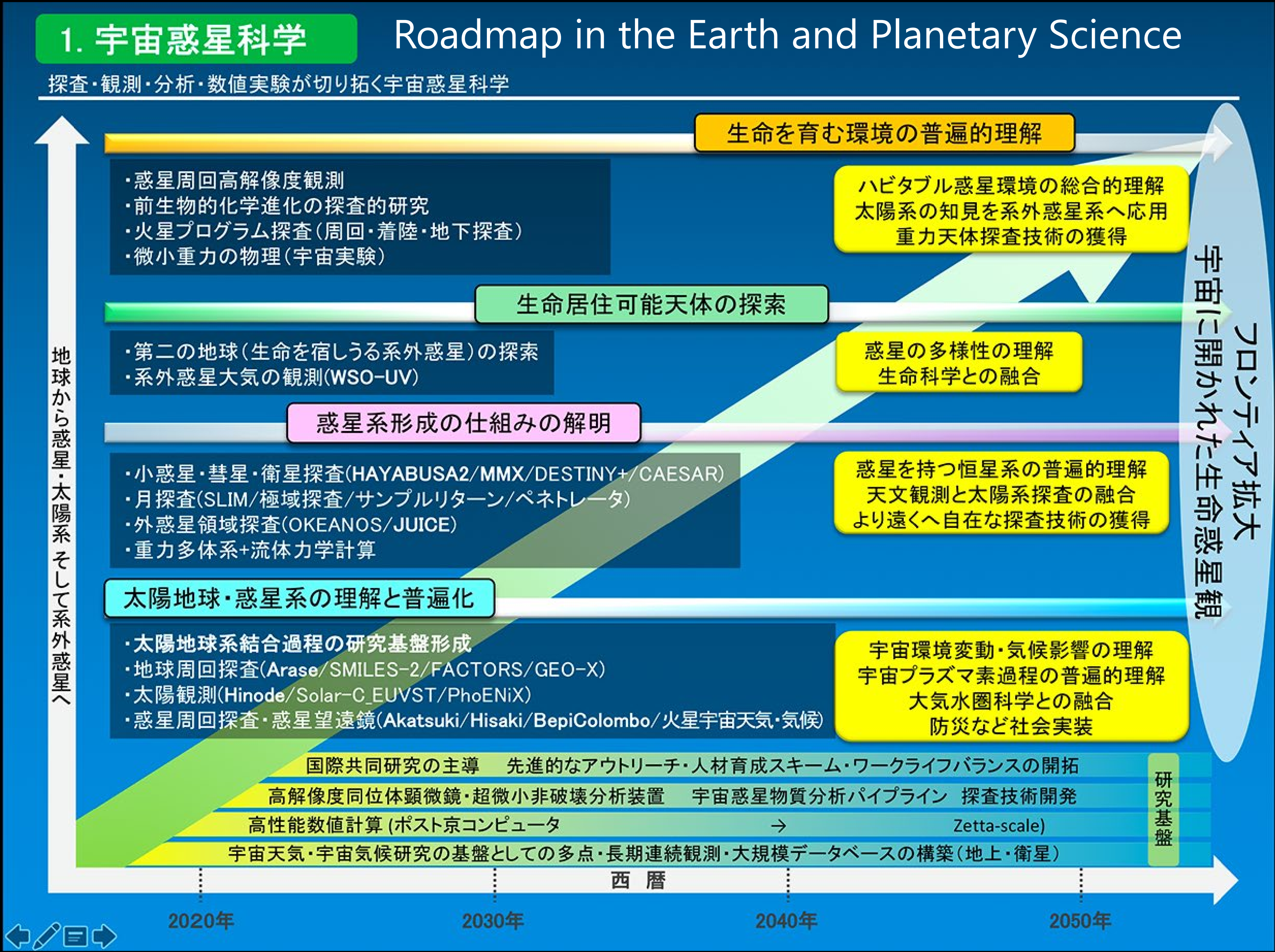
ngVLA



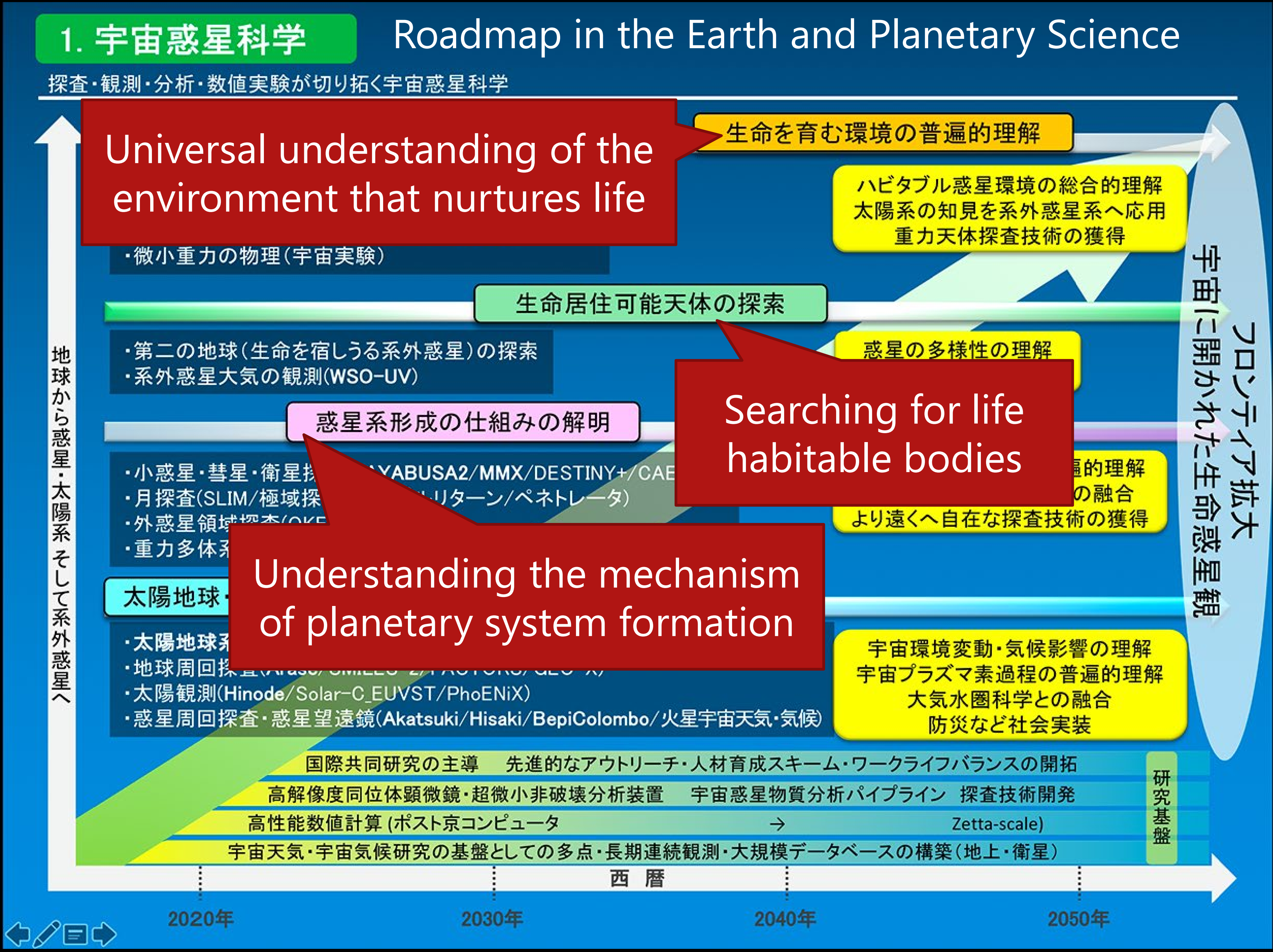
van der Marel et al. (2019)

The challenges are the same. It would be better to consider that there is no boundary between astronomy and planetary science, in terms of observational strategy, research focus, etc. There may still be some differences between our languages.

Science and Dreams Roadmap
地球惑星科学分野の
科学・夢ロードマップ
http://www.jpgu.org/2019roadmap/p/



The challenges are the same. It would be better to consider that there is no boundary between astronomy and planetary science, in terms of observational strategy, research focus, etc. There may still be some differences between our languages.



Science and Dreams Roadmap
地球惑星科学分野の
科学・夢ロードマップ
http://www.jpgu.org/2019roadmap/p/

Notes

This talk does not consider the following points at all.

- Technical feasibility has a significant impact in the discussion of the implementation of plans.
- There is no correlation between the realization of a plan and the number of researchers who support it currently, as long as there are enough researchers who will be able to advance the science with the plan in the future, and there is a good team to manage the plan. A plan can evolve. A good plan will attract researchers and lead to a development of the field.
- We cannot do everything. What are the strengths of Japan so far? How do we build on Japan's strengths in science and in the technical development?