

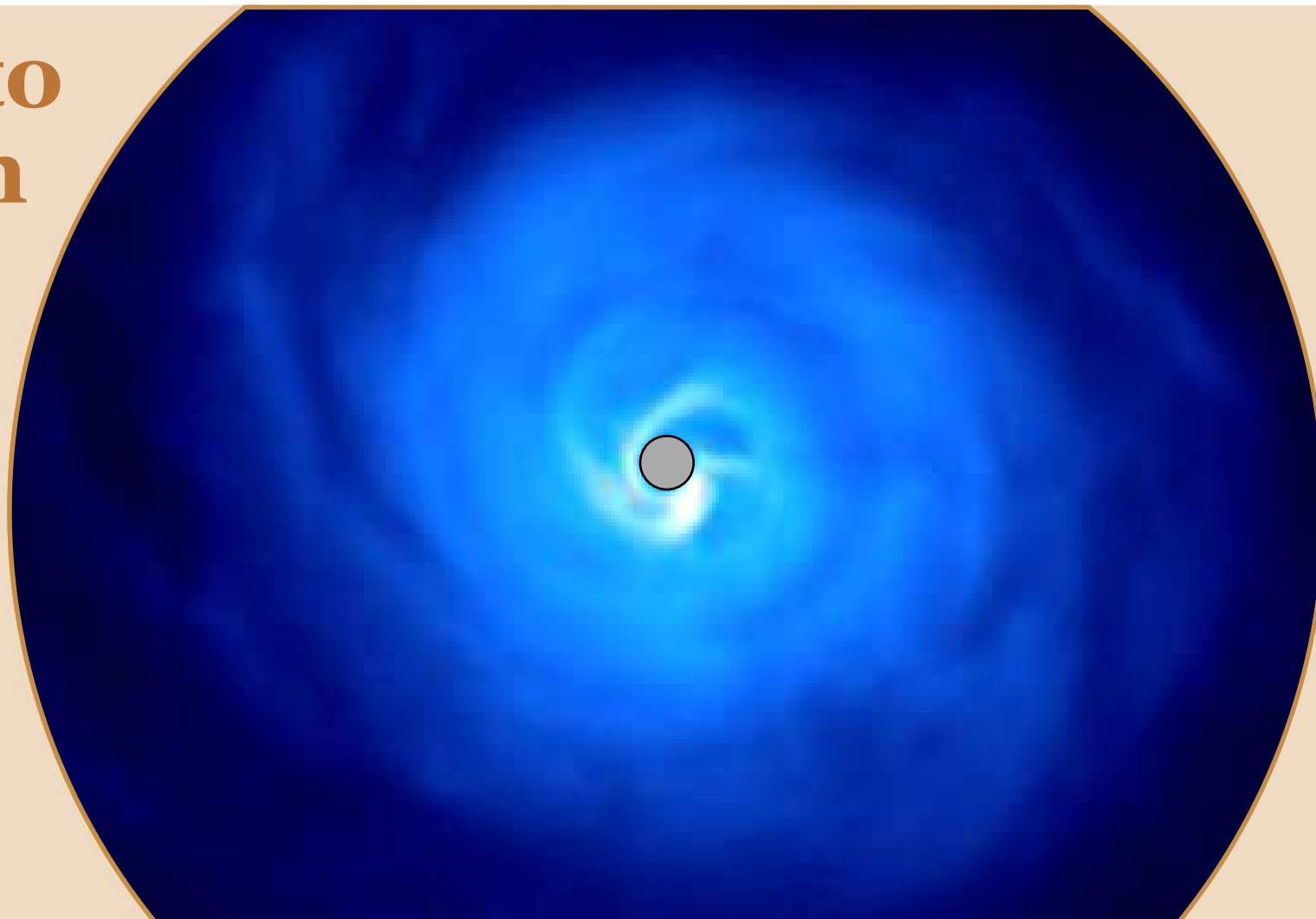
One step closer to planet formation

Antonio Garufi

STILES fellow

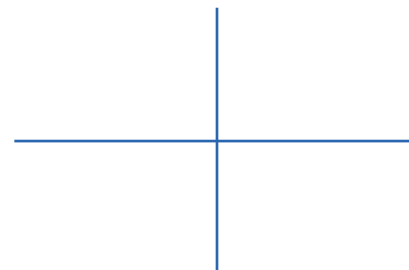
*Istituto di Radioastronomia
(IRA), Bologna - INAF*

with S. Pérez, D. Fedele, J.D. Ilee,
P. Pinilla, D. Price, M. Villenave,
and the *Cradle of Life* working group



Most solar-like stars host planets.

Planetary systems are diverse.



Planet-forming disks live a few Myr.

The meter barrier halt dust growth.

In (and from) a nutshell, planet formation is...

Most solar-like stars host planets.

...efficient.

Planet-forming disks live a few Myr.

...fast.

Planetary systems are diverse.

...complex.

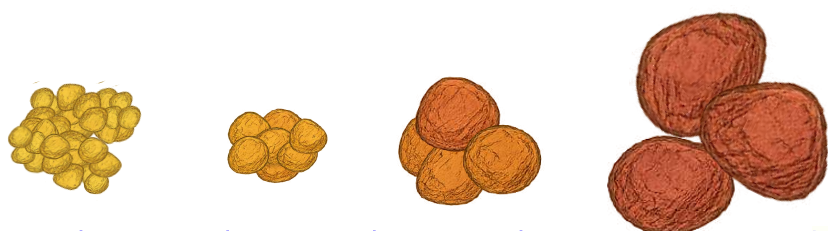
The meter barrier halt dust growth.

...not understood.

The growth of ISM dust grains to planets involves **14 orders of magnitude**.

Dust growth from coagulation

Gravitational growth Gas accretion



1 μm

1 mm

1 m

1 km

1 Mm

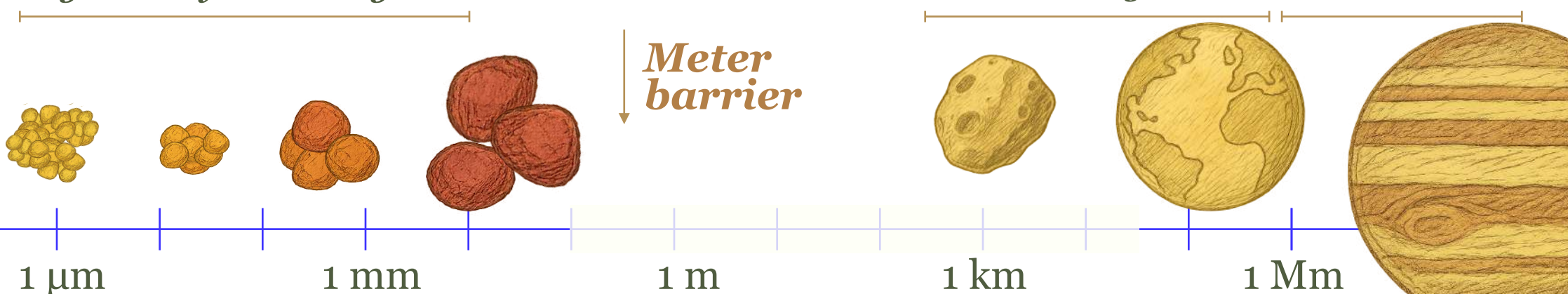
The growth of ISM dust grains to planets involves **14 orders of magnitude**.

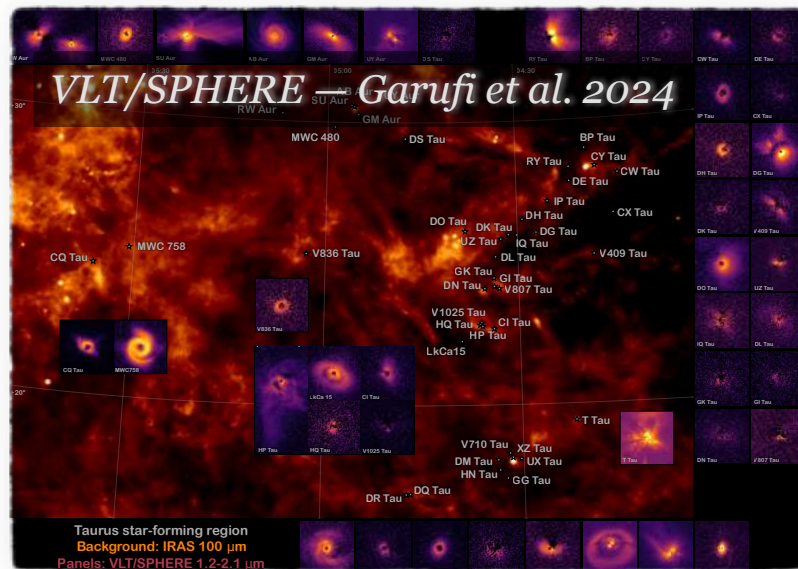
The most critical range is currently **not observable**.

Pebble accretion?
Core accretion?

Dust growth from coagulation

Gravitational growth Gas accretion

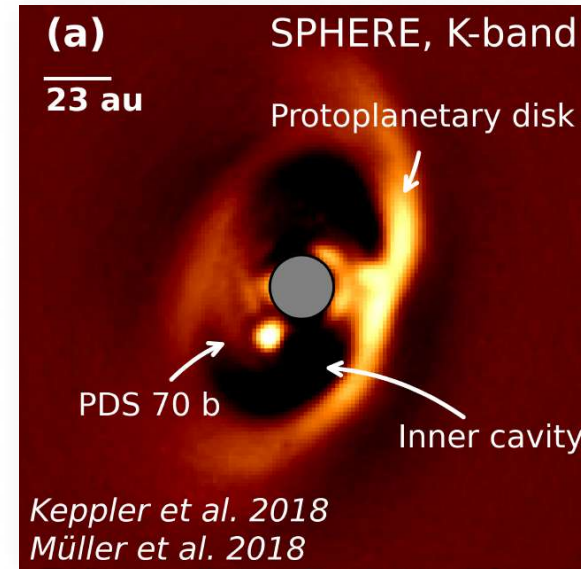




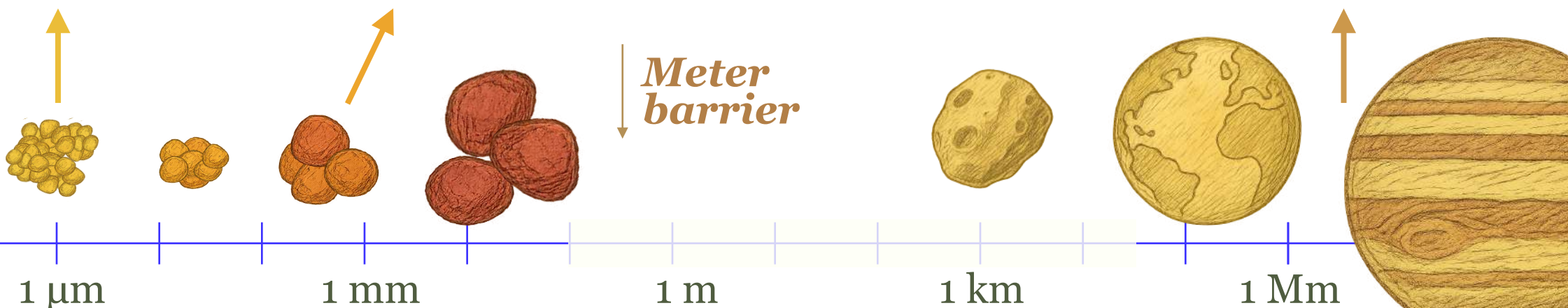
Near-IR scattered light



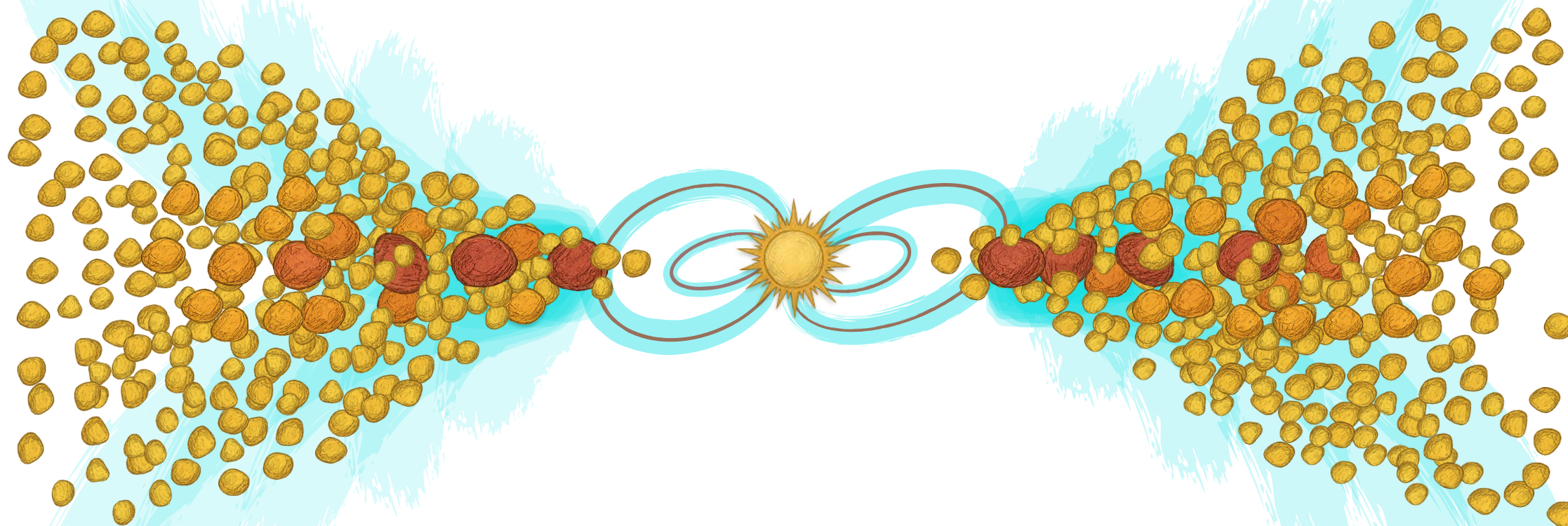
ALMA thermal continuum



Near-IR thermal continuum



SKA will be the first instrument to resolve **pebbles**.



Disk midplane, ionized gas, and **moon-forming** disks are also accessed.

Cradle of Life

Science Working Group



The Square Kilometer Array Observatory (SKAO) is a global enterprise to build the largest scientific instrument on Earth, both in physical scale and in terms of the volume of data it will generate. Consisting of two telescope arrays located respectively in Australia and South Africa and managed from the SKAO headquarters in the UK, the SKAO promises to revolutionize our understanding of the universe. The science case for the SKAO has the potential to appeal to users well beyond their radio astronomy community, spanning across a wide range of areas of physics, cosmology and astrophysics. Science working groups (SWGs) and Focus Groups (FGs) covering all these areas have been set up to further evolve the SKA science case, providing a conduit for interaction between the SKAO science team and the astronomical community. This banner provides a summary of the Cradle of Life Science Working Group.

1. Understand Planet Formation
 Coagulation of μm -sized particles in circumstellar discs is the first step to planet formation. Crossing the 'cm barrier' is a challenge for theoretical models. Both the frequency coverage and resolution of SKA is required to observe cm-sized grains at solar system scales and in the planet-forming 'miles of disc'.
 Grain growth toward planet formation
 SKA1-MID
 Kuiper Belt
 Solar System
 Opacities of various grain size distributions. The observing wavelengths of ALMA/NOEMA are complementary with SKA1 sensitive to the largest grains (a few μm).
 Simulated SKA1-MID observations (Band 5b, 67 mas) of a protoplanetary disc host to three giant planets (left), with a representation of our own Solar System on the same scale (right). Credit: John D. Lee, University of Leeds (lee et al. 2020, MNRAS, 498, 5116).

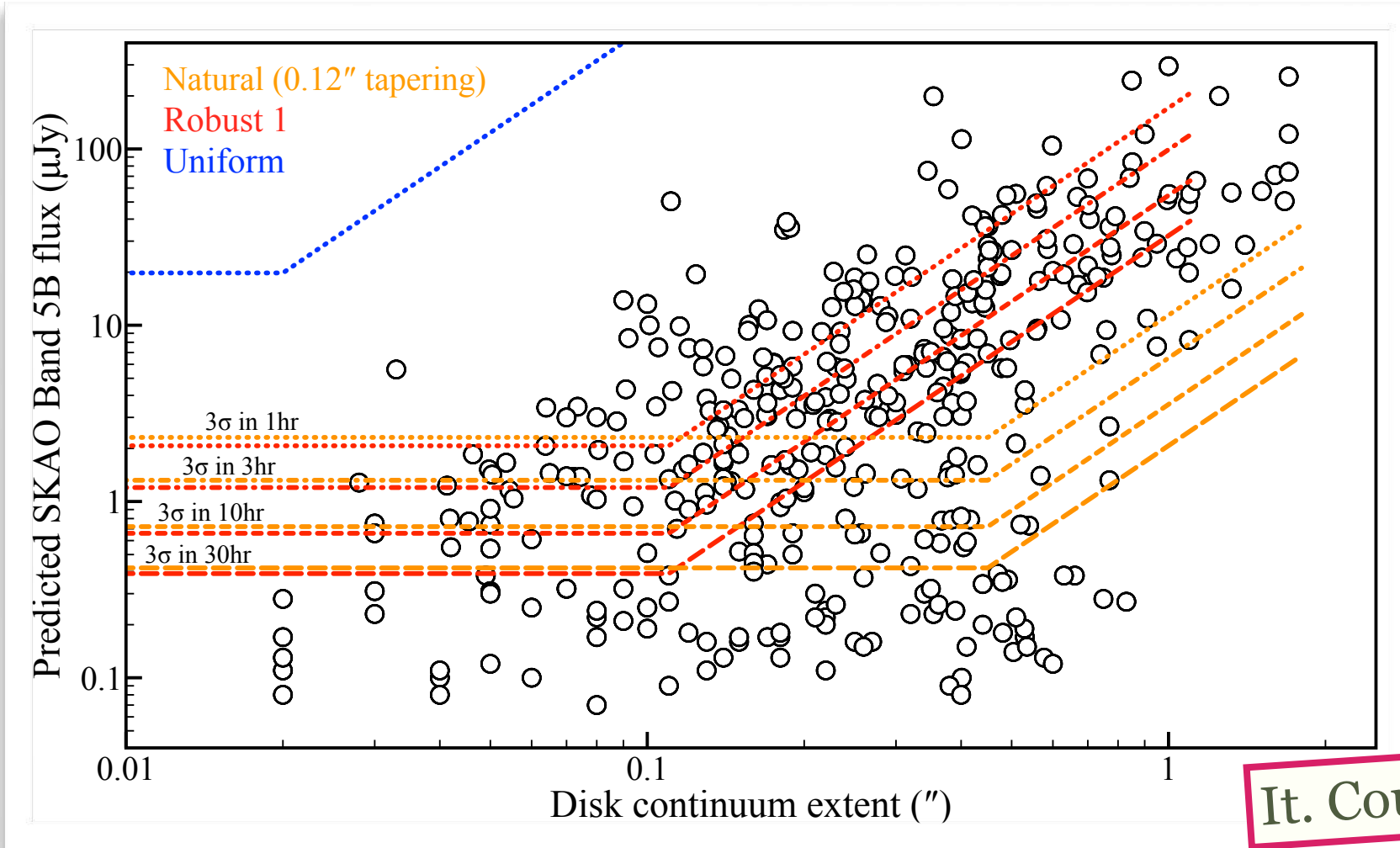
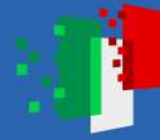
2. Detect and characterize large molecules in planet-forming regions
 Organic building blocks relevant in cosmochemistry and biology (e.g. sugar-like species, molecules with peptide-like bonds) are found in primordial meteorites and analogs of the young Solar System. Spectra of chemically rich sources at millimetre wavelengths suffer from line blending and line confusion. Spectra will be less crowded at cm wavelengths, where, additionally, dust emission is optically thin, making identification of pre-biotic molecules more straightforward.
 Credit: S. Sauer (MNRAS 2020)

3. Detection and characterization of exoplanets
 Magnetized planets such as the Earth and the giant planets produce aurorae (known as northern/southern lights or aurora borealis/australis) near the magnetic poles, accompanied by bright radio emissions. The observation of such radio emissions provides a wealth of information on the planetary interior, where the magnetic field is produced, and its magnetosphere, which shields the planet from the high velocity particles constantly ejected by the Sun, the so-called solar wind. This shielding has strong implications for habitability as it prevents the atmosphere from being blown away by the Sun and ensures a low level of surface radiation. By analogy, planets around other stars (exoplanets) may also emit radio emission that helps us understand their interiors and possibly whether some of them are habitable. There are hundreds of planetary systems within 50 light years of the Sun and the SKA1-Low will be able to observe. The signal detected from these systems will serve to characterize exoplanet magnetospheres and how exoplanets interact with their host star.
 Jupiter's magnetic field, after interplanetary scintillation. Credit: NASA

4. Search for ExtraTerrestrial Intelligence (SETI)
 SKA1 will be capable of detecting emission sources analogous to high-power terrestrial transmitters such as airport radars. At 10 pc distance, a detection could be made in 15 minutes. With longer integrations, unbiased surveys of all (~10,000) stars within 60 pc are feasible. In addition, we will, for the first time, have the sensitivity to detect "leakage" transmissions from one-directional transmitters with power close to the brightest transmitters on Earth. Currently, pathfinder interferometric SETI work is being carried out on MeerKAT as well as the Very Large Array (VLA).
 Credit: S. Sauer (MNRAS 2020)

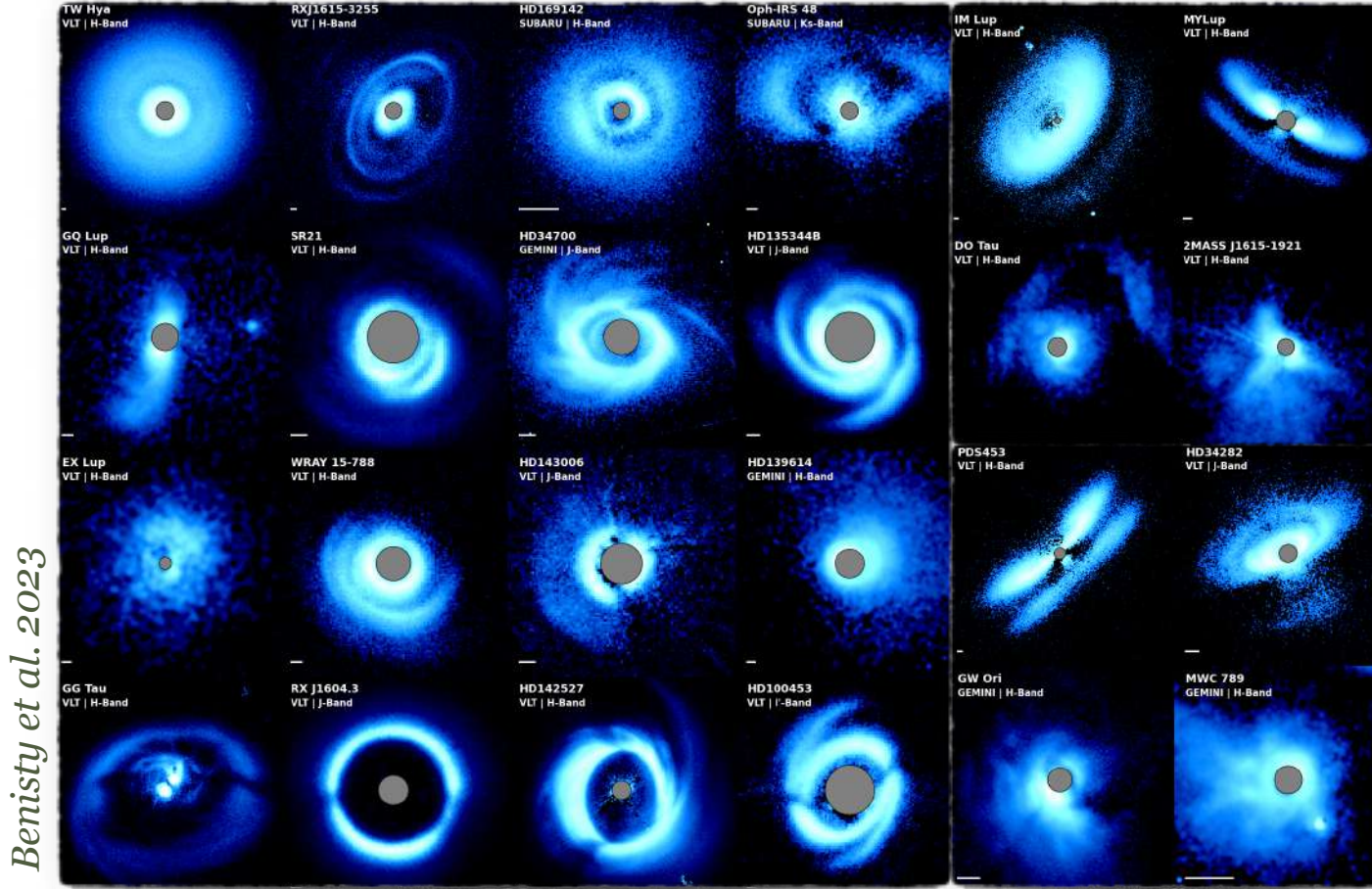
5. Understand our Solar System and its origin
 The SKA will be especially relevant for characterising comets, trans-Neptunian objects (TNOs), and centaurs, the "primordial building blocks" from which the Solar System was formed. It will be possible to observe some key species in cometary atmospheres, such as OH and ammonia, and complex molecules in exceptionally active comets. The physical, thermal and compositional properties of TNOs and centaurs will also be observed with SKA. The radiation belts of Jupiter and Saturn will be characterized to obtain information about their interiors. It will also be possible to detect and monitor lightning activity in the atmospheres of all solar system planets and some moons.
 Microwave image of comet 67P (Churyashra) (A. Zieger) | Angular size of the central Oort cloud (A. Zieger) | Jupiter at 10 pc with the VLA (NASA)

- ### “Advancing Astrophysics II”
1. Chenoa D. Tremblay – *Searching for ET Intelligence*
 2. Antonio Garufi – *Demographics of planet-forming disks*
 3. Yin hao Wu – *Substructures and planet-disk interactions*
 4. Greta Guidi – *Ionised gas emission from disks*
 5. Linda Podio – *Disk Chemistry*
 6. Giovanni Sabatini – *Jets and outflows in YSOs*
 7. Eleonora Bianchi – *Chemical complexity in star formation*
 8. Pablo Santos-Sanz – *Trans-Neptunian Objects*
 9. Jan Forbrich – *SKA-ALMA synergies*
 10. Rob Kavanagh – *Exoplanets and brown dwarfs*
 11. Harish Vedantham – *Star-planet interactions*

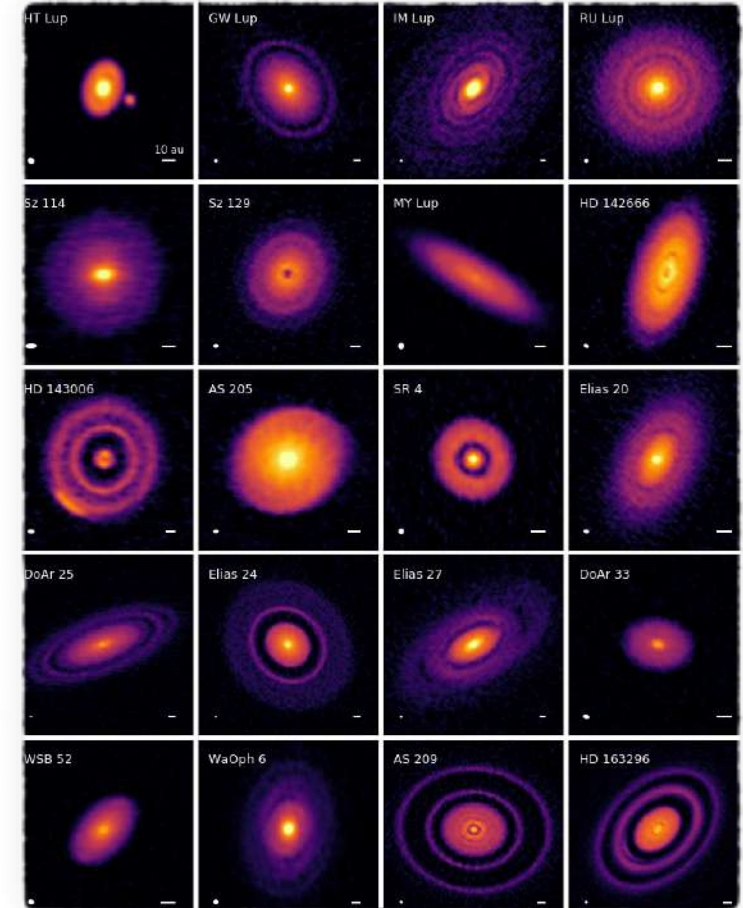


Garufi et al., 2026,
SKAO white book

It. Could. Work.



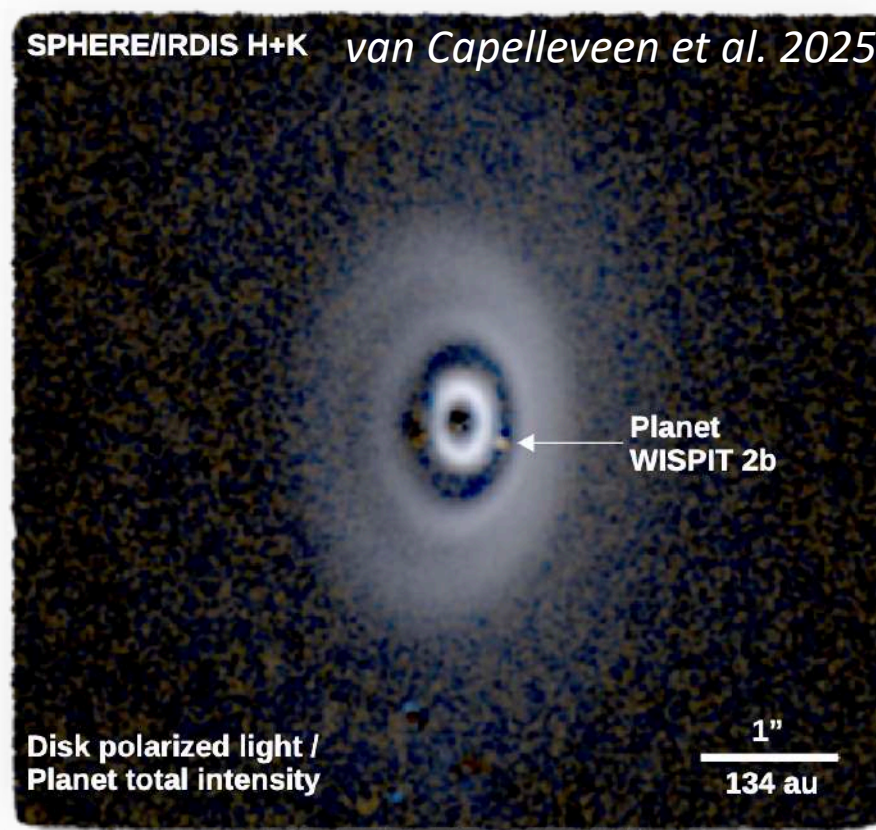
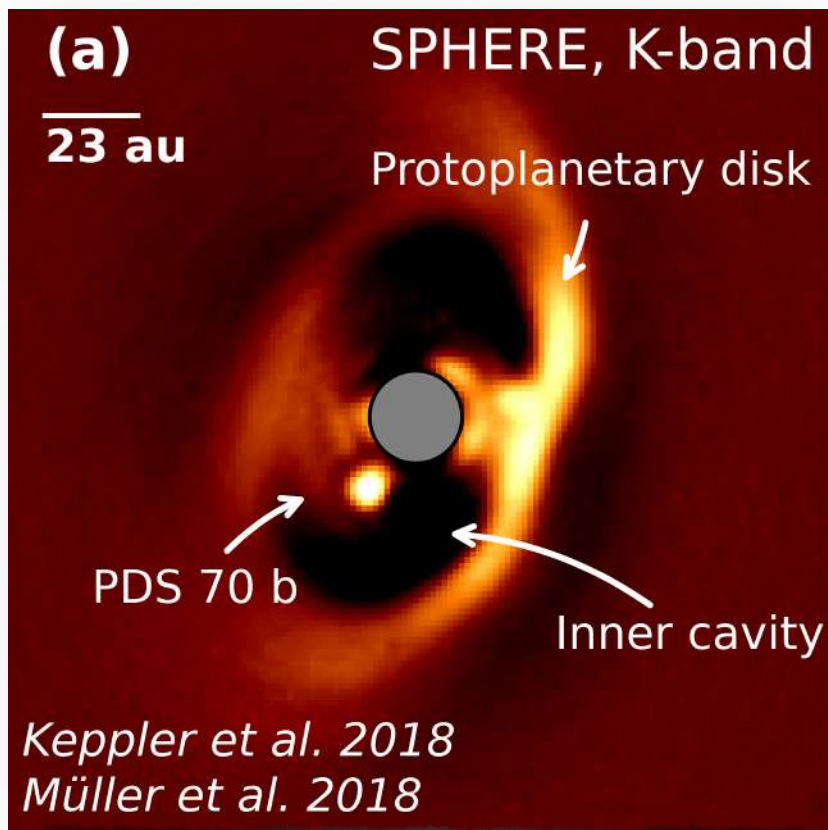
Benisty et al. 2023



Andrews et al. 2018

The census from VLT/SPHERE and ALMA suggests that disk **substructures** are ubiquitous. Some of these are likely due to embedded **protoplanets**.

Yet, protoplanets remain very **elusive** as only 2-3 are confirmed in 15 years search.



Protoplanets are not detected because they:

are **cold** (small)



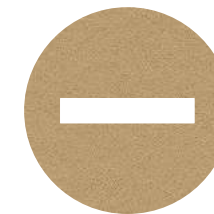
are heavily **extincted**



are **closer in**



have **not formed** yet



Protoplanets are not detected because they:

are **cold** (small)



Longer wavelengths ($\geq 4-5 \mu\text{m}$) needed.

JWST
VLT/ERIS (PETS, PI: Garufi)
E-ELT Metis

are heavily **extincted**



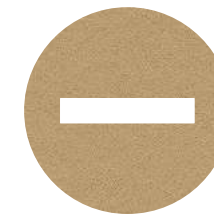
are **closer in**



Larger mirrors needed.

E-ELT
Micado and Metis

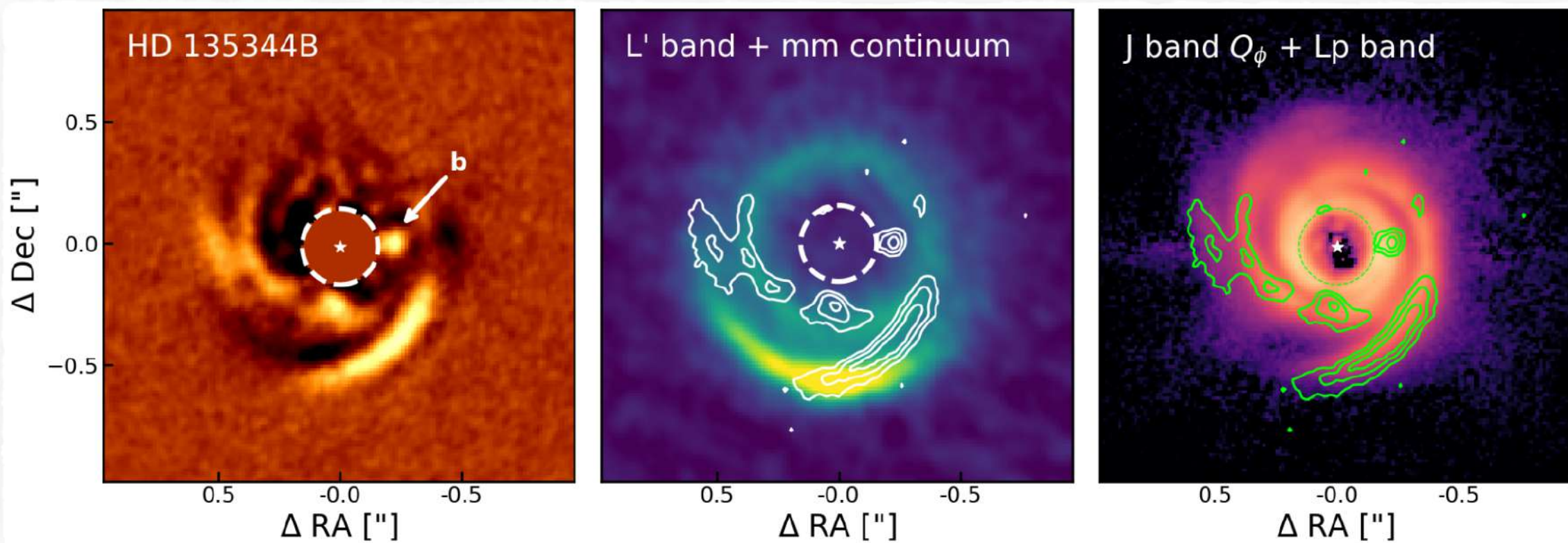
have **not formed** yet



Theories and measures are wrong. Need to fix.

?

One **protoplanet** candidate is detected near a launching point with VLT/**ERIS**.
(*Francesco Maio et al. 2025*)



Pebbles and **protoplanets**: ELT and SKA will revolutionize the field of the planet formation.

