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ACCRETION DISK MODELS

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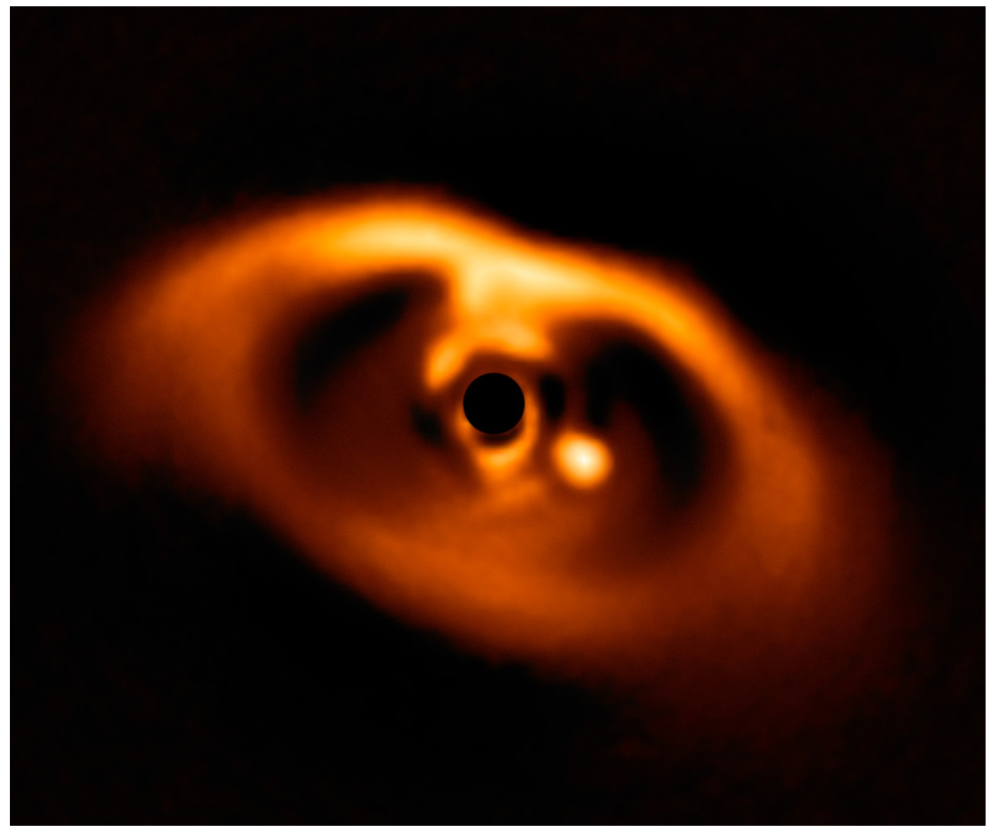
EARTH AND BEYOND

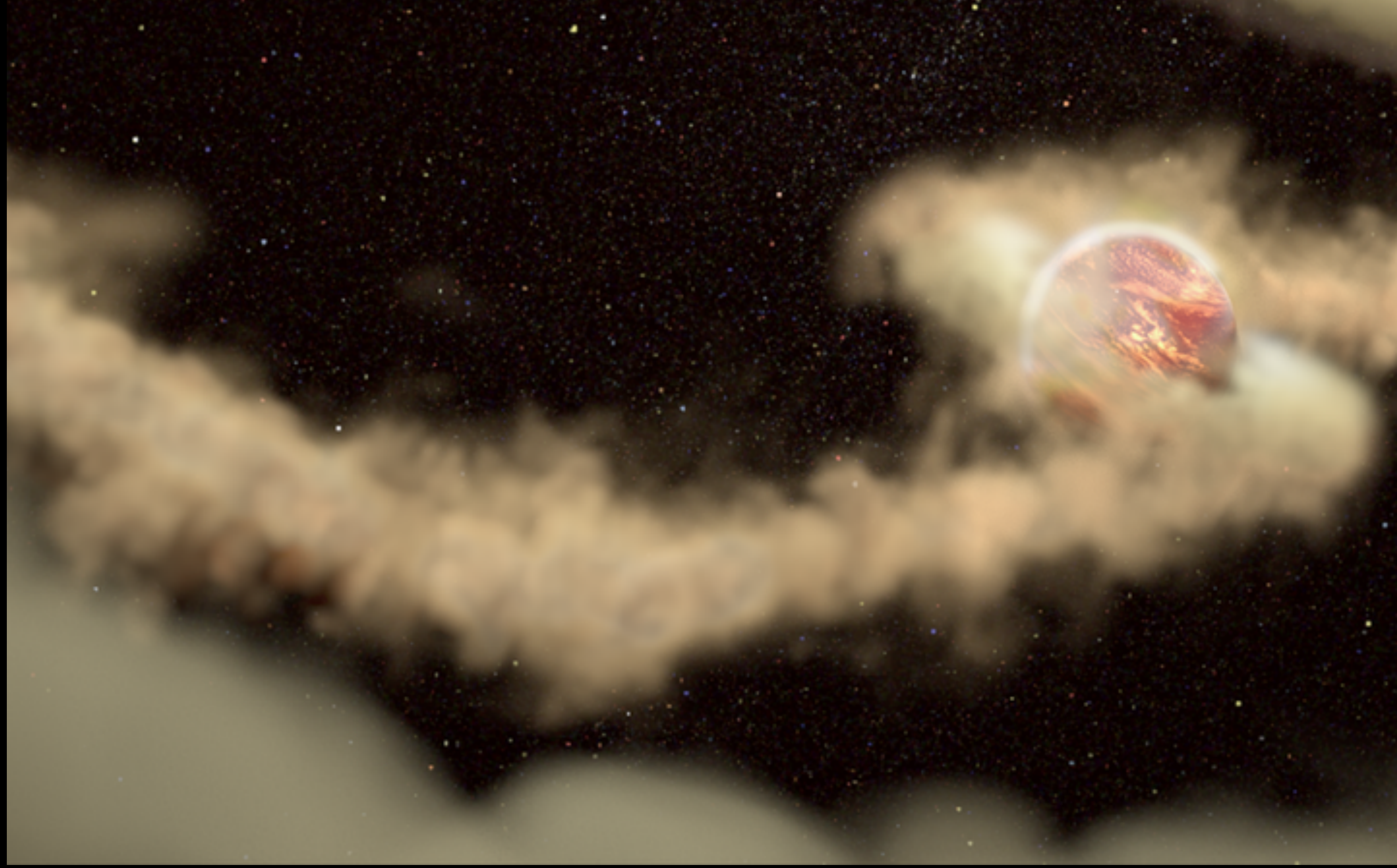
Planetesimals form via collisions amongst the debris orbiting a star.
Image Credit: Image Credit: ISAS/JAXA



The protoplanetary disk of PDS 70 with new planet PDS 70 b
Image Credit: ESO/A. Müller et al. 2018

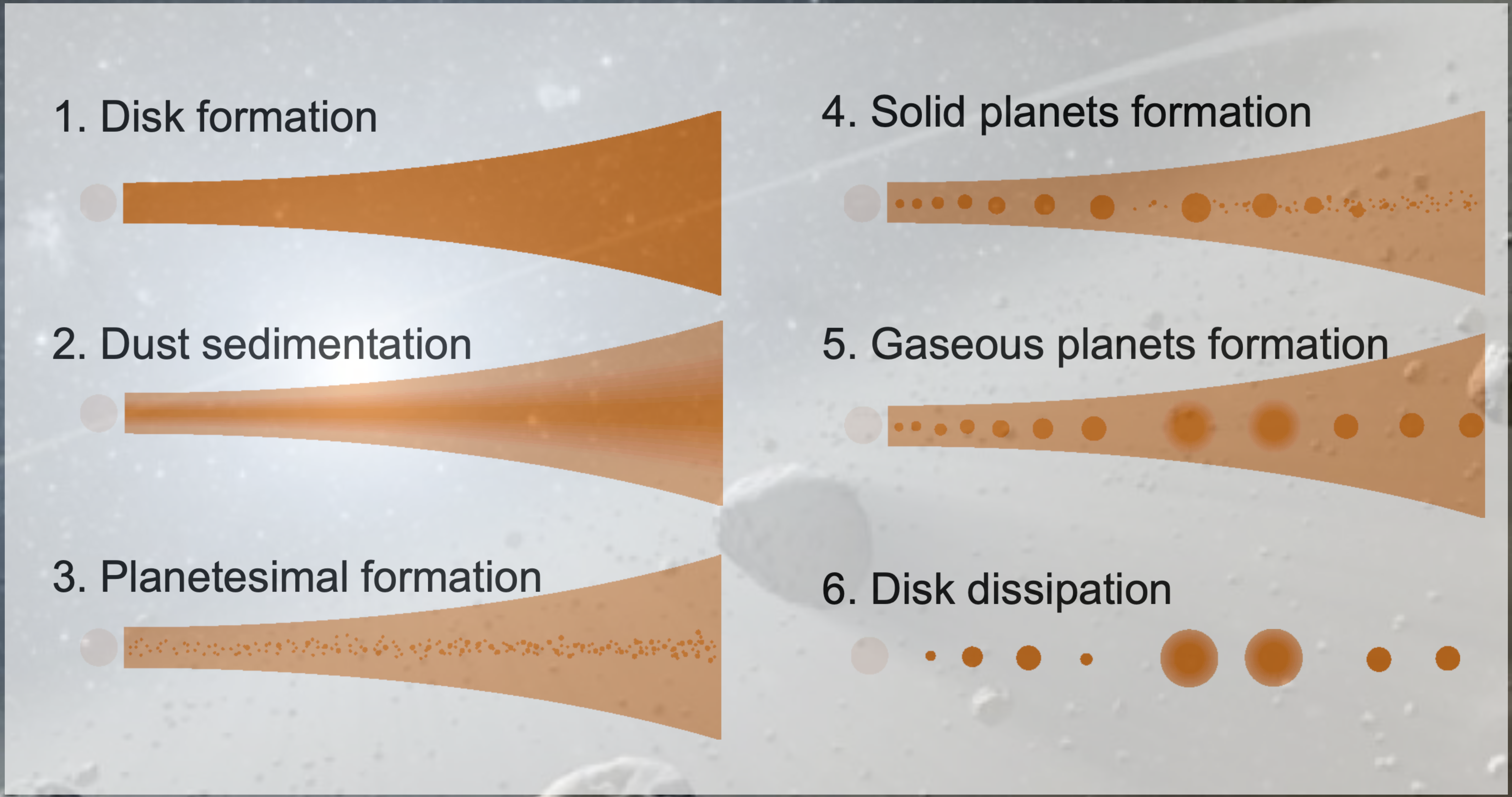
PROTOPLANETARY DISC

- GRAVITATIONAL INSTABILITIES IN MOLECULAR CLOUDS OF GAS AND DUST GRAINS LEAD TO GRAVITATIONAL COLLAPSE, FRAGMENTATION, AND ACCRETION
- INSIDE THE DISK, GAS CLOSER TO THE CENTRE ROTATES MORE RAPIDLY THAN IN THE OUTER REGIONS. IT THEN BREAKS DOWN INTO TURBULENT FLOW



Artist's rendering of the planets orbiting PDS 70
Image Credit: J. Olmsted (STScI)

PLANETARY FORMATION : CORE ACCRETION MODEL

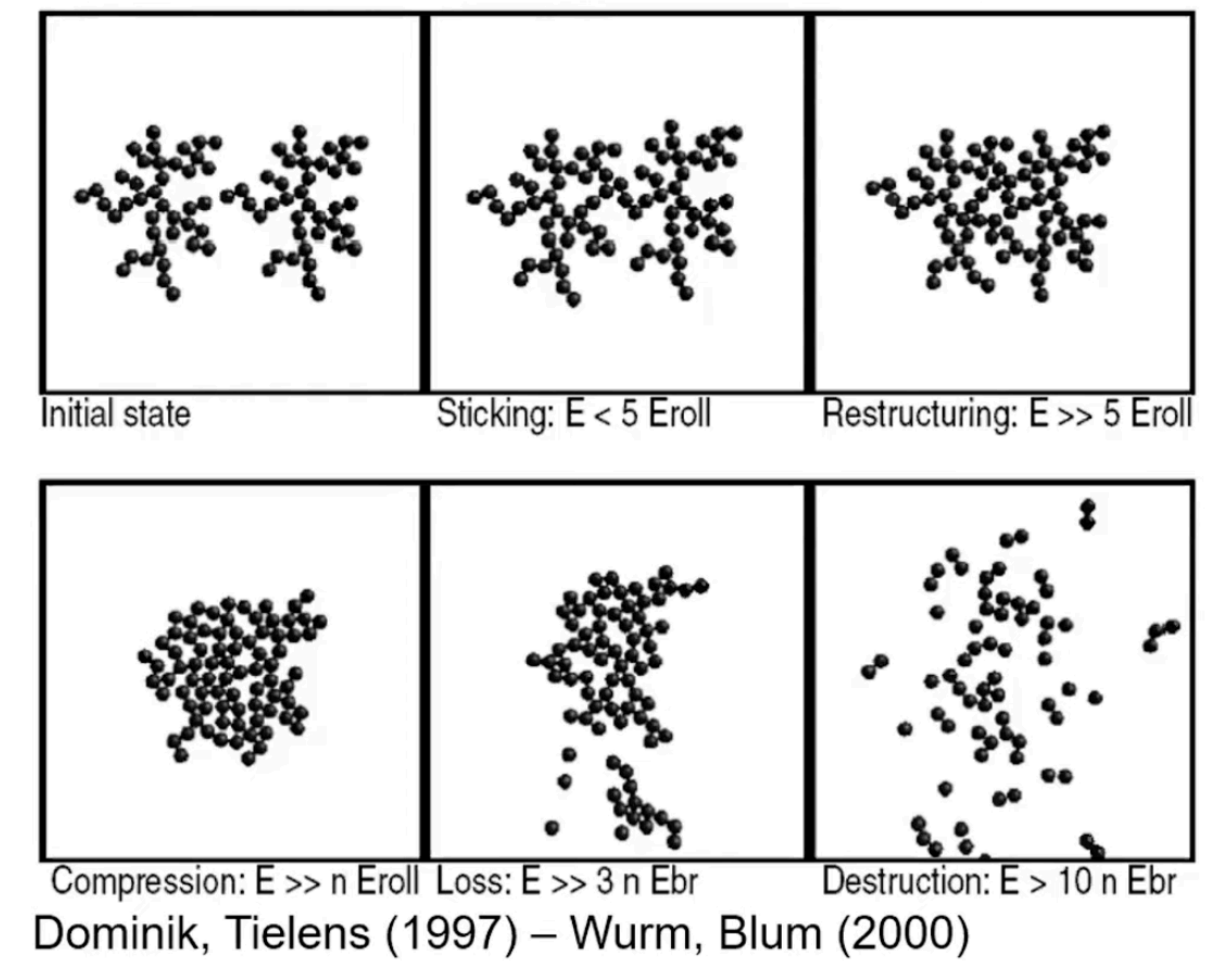


What is a planetesimal?

- **Building blocks of planets**
- **Kilometer-sized objects massive enough to attract each other by gravity (two-body encounters)**
- **Assembled from colliding dust grains**

FORMATION OF FRACTAL DUST PARTICLES

- VELOCITY DIFFERENCE BETWEEN SMALL GRAINS AND METER-SIZED BOULDERS BECOMES TOO LARGE

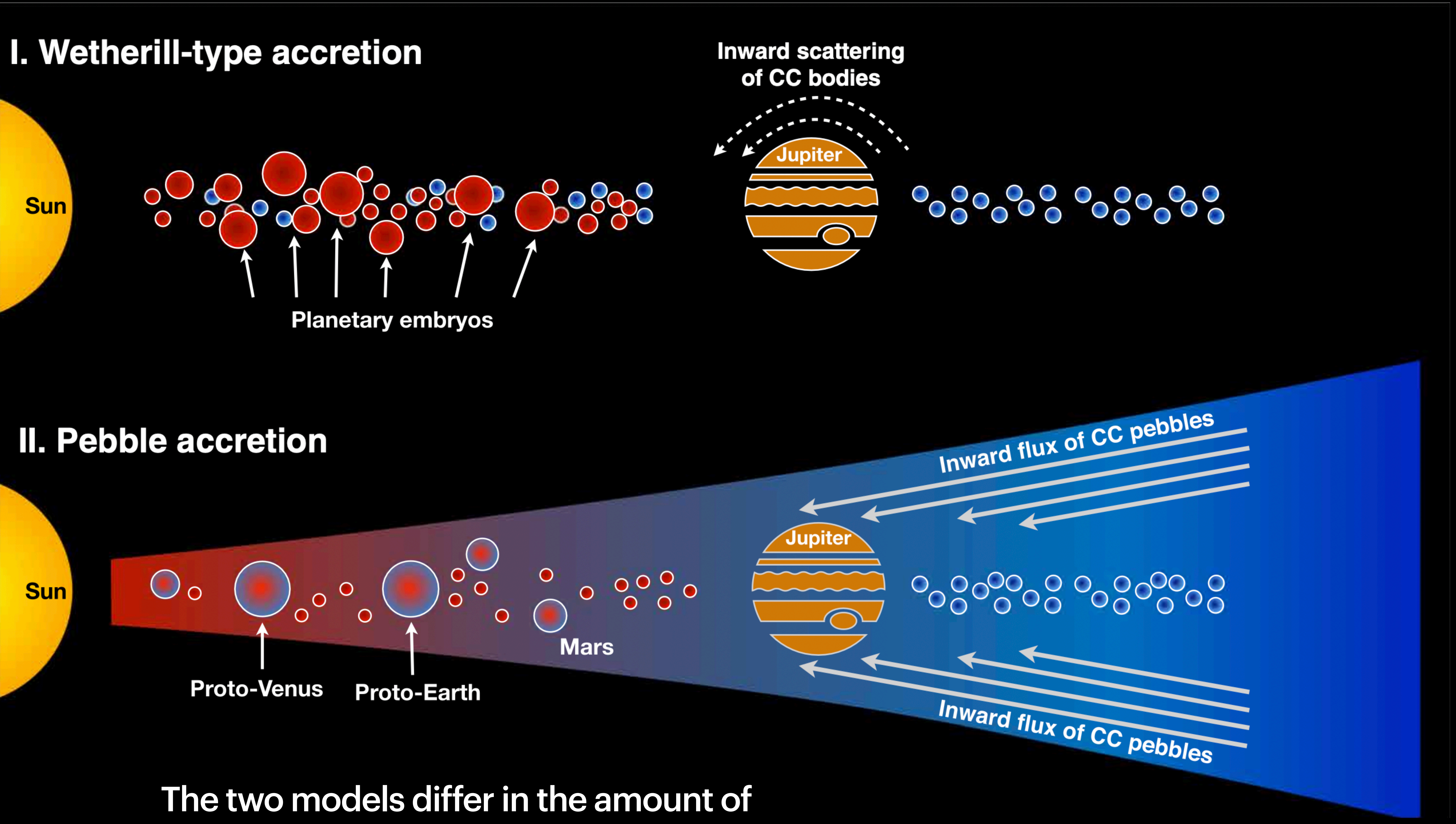


This Allende meteorite (1969)
CAI (*Ca-Al-rich Inclusion*)
Oldest material in the solar system

FORMATION OF METER-SIZED BODIES

- METER-SIZED BODIES GROW DUE TO ATTACHMENT OF GRAINS OF SMALLER BODIES/GRAINS FROM THE PROTOSOLAR NEBULA BECAUSE OF DIFFERENT ORBITAL VELOCITIES (~ 10^4 YR).

POSSIBLE SCENARIOS OF TERRESTRIAL PLANET FORMATION



The two models differ in the amount of outer solar system material accreted by the terrestrial planets

Burkhardt, C. et al. (2021)

OLIGARCHIC GROWTH

The terrestrial planets are formed by mutual collisions among Moon- to Mars-sized planetary embryos after the gas disk dissipated and accreted only a small fraction of CC planetesimals, which were scattered inward during Jupiter's growth and/or putative migration.

PEBBLE ACCRETION

Alternatively, the terrestrial planets may have formed within the lifetime of the gas disk by efficiently accreting "pebbles" from the outer solar system, which drift sunward through the disk due to gas drag. synthetic isotope anomalies.

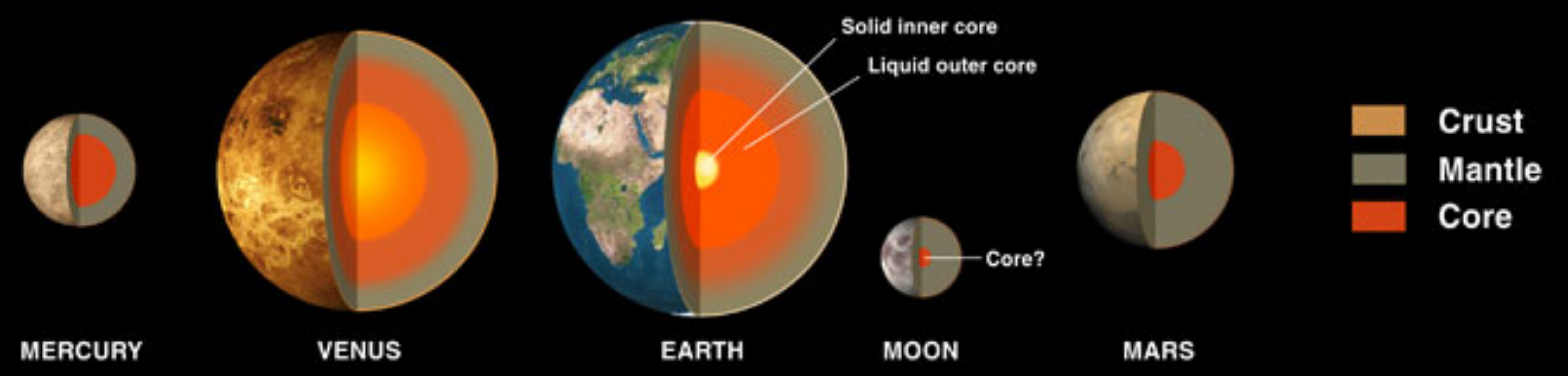
ACCRETION MODEL

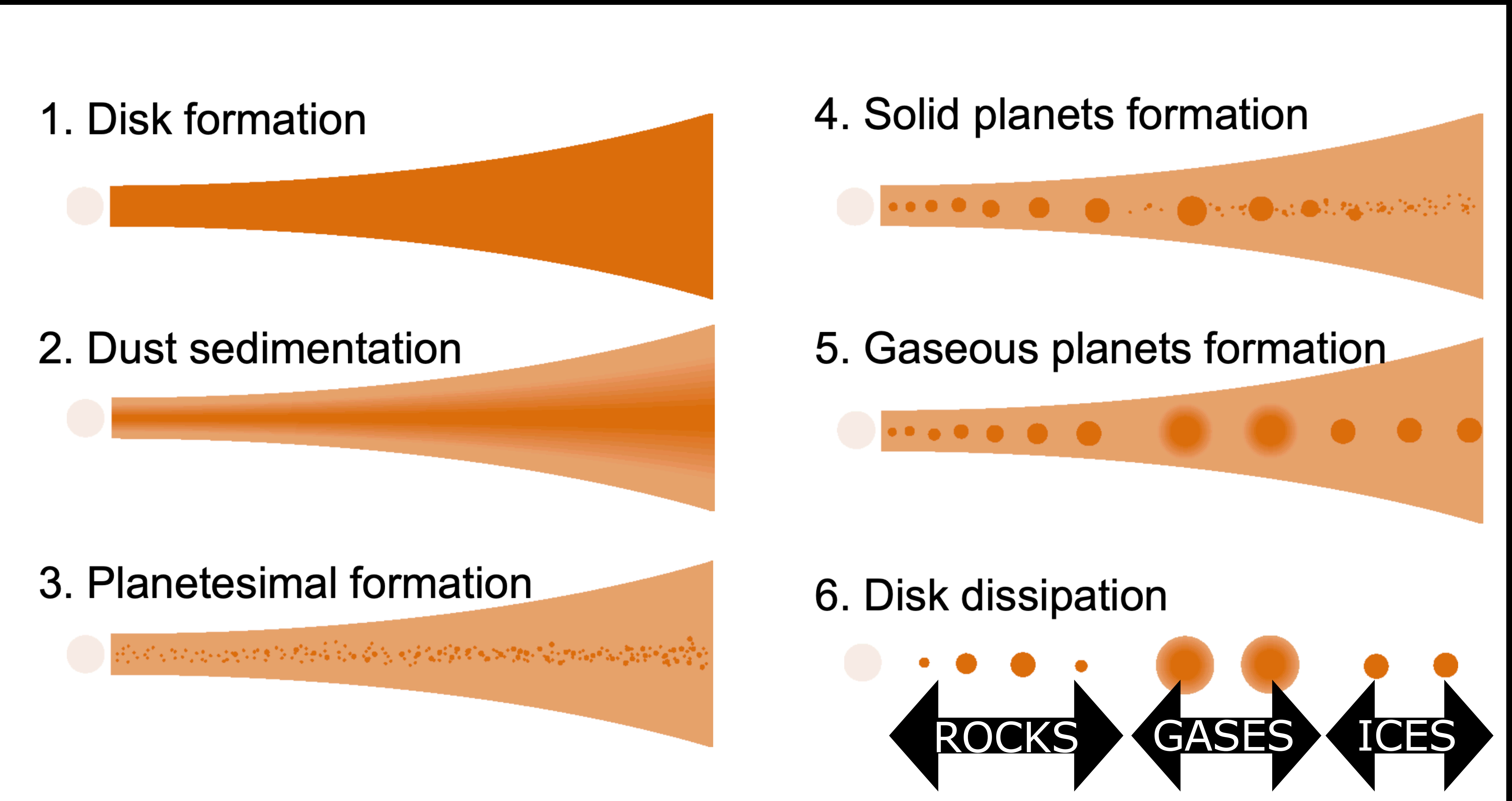
◉**CAN EXPLAIN**

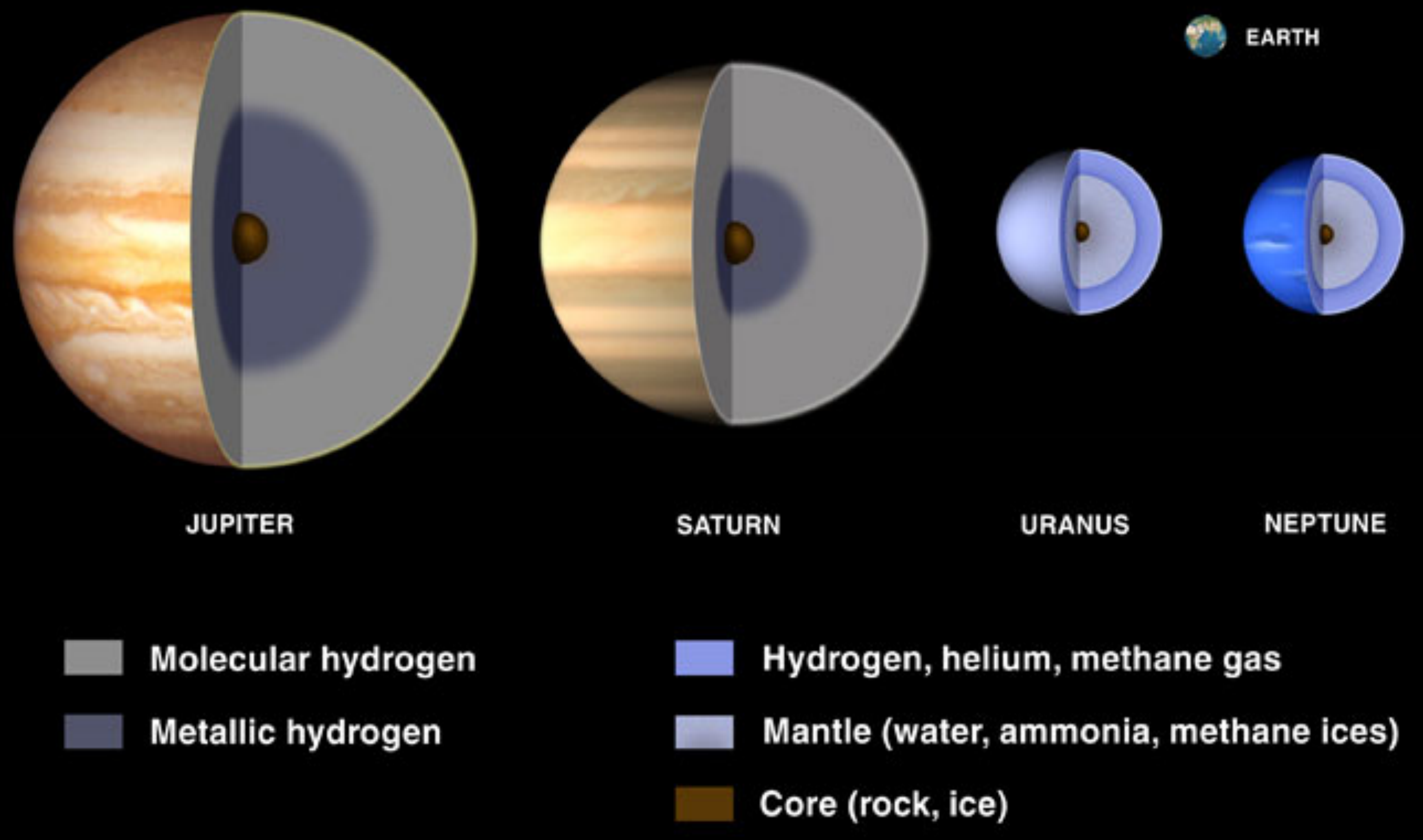
* THE FORMATION OF BOTH GAS AND ICE GIANTS
* THE CORRELATIONS BETWEEN STELLAR METALLICITY AND GIANT PLANET OCCURRENCE

◉**CHALLENGES:**

* PLANETESIMAL FORMATION AND EARLY EMBRYO GROWTH
* EXISTENCE OF THE PLANETS AROUND STARS OF VERY LOW HEAVY-ELEMENT ABUNDANCE
* MASSIVE GIANT PLANETS BEYOND 20 AU







PLANETARY FORMATION : DISC INSTABILITY MODEL

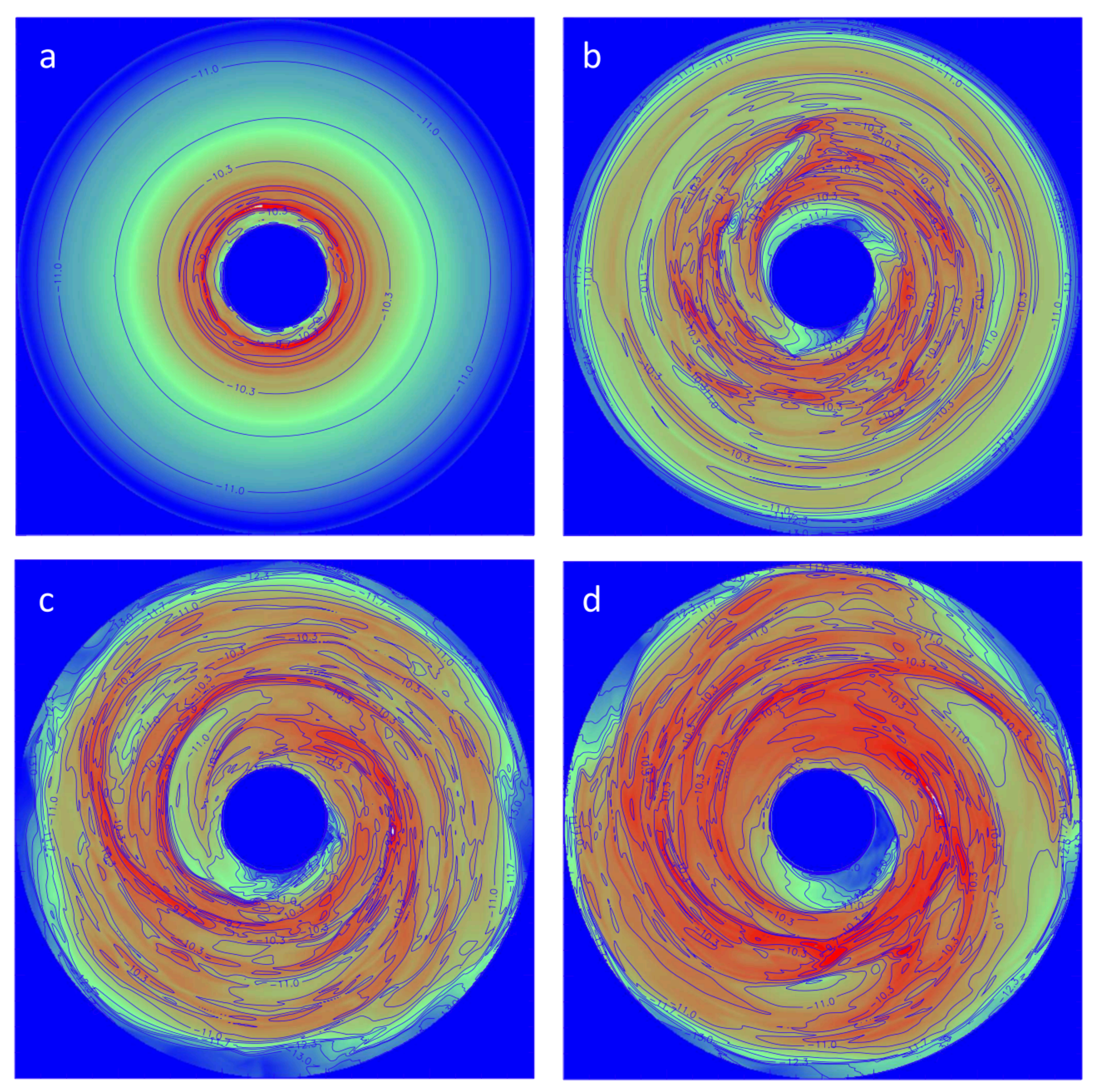
THE GIANT PLANETS COULD FORM BY CONTRACTION OR RAPID, SINGLE-STEP COLLAPSE OF GASEOUS CONDENSATIONS IN A MASSIVE SELF-GRAVITATING DISK WITH THE SPIRAL DENSITY WAVES

UNSTABLE DISKS WOULD EVOLVE THROUGH THE FORMATION OF SPIRAL DENSITY WAVES

WAVES WOULD TRANSPORT ANGULAR MOMENTUM, LOWERING THE SURFACE DENSITY AND ENHANCING STABILITY, BUT ALSO LEAD TO DISSIPATION AND HEATING.

FRAGMENTATION WOULD DEPENDS ON WHETHER THE DISK SELF-GRAVITY CAN OVERCOME THE THERMAL PRESSURE IN THE DISK, WHICH DAMPING THE GROWTH OF PERTURBATIONS.

“The Effect of the Approach to Gas Disk Gravitational Instability on the Rapid Formation of Gas Giant Planets”, Boss (2019)



Equatorial (midplane) density contours for model after (a) 38.5 yr, (b) 162 yr, (c) 318 yr, and (d) 422 yr. The disk has an inner radius of 4 au and an outer radius of 20 au.

The boundaries of the boxes represent where different chemical species are condensing in the atmosphere of a planet at a stellar flux, according to equilibrium chemistry calculations (Kopparapu et al. 2018)

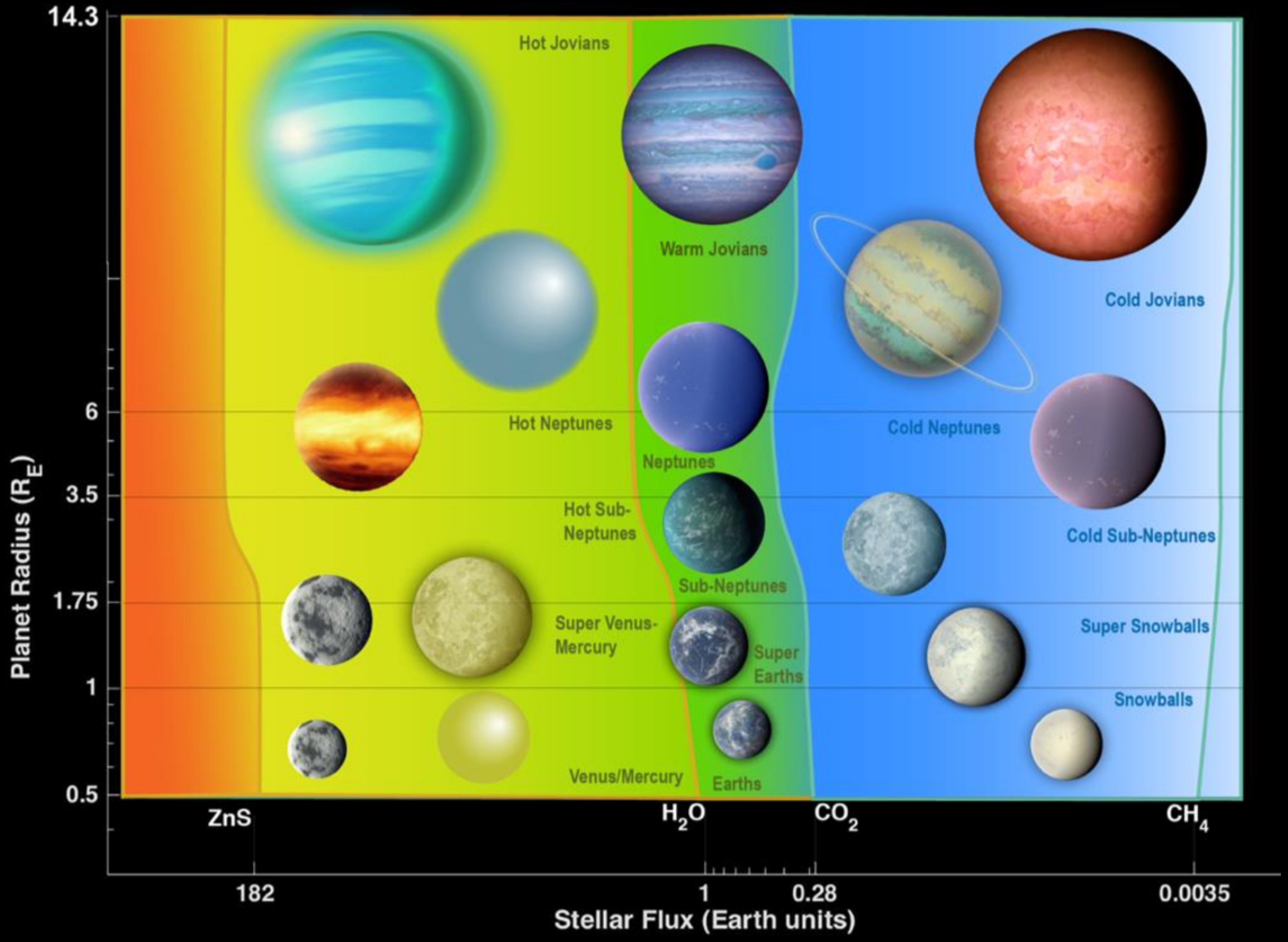
DISC INSTABILITY MODEL

◉**CAN EXPLAIN**

* A VARIETY OF OUTCOMES - GAS GIANTS WITH AND WITHOUT CORES, METAL-RICH AND METAL-POOR GAS GIANTS, BROWN DWARFS
* CAN TAKE PLACE AT LARGE DISK RADII AND IN LOW METAL ENVIRONMENTS

◉**CHALLENGES:**

* THE QUESTIONABLE OPPORTUNITIES FOR PROTOPLANETS TO SURVIVE TIDAL DISRUPTION AND RAPID INWARD MIGRATION
* CAN'T EASILY EXPLAIN INTERMEDIATE-MASS PLANETS OR THE CORRELATION
* CAN'T EASILY EXPLAIN GIANT PLANET OCCURRENCE AND STELLAR METALLICITY



PROTOPLANETARY DISKS SEEN BY ALMA

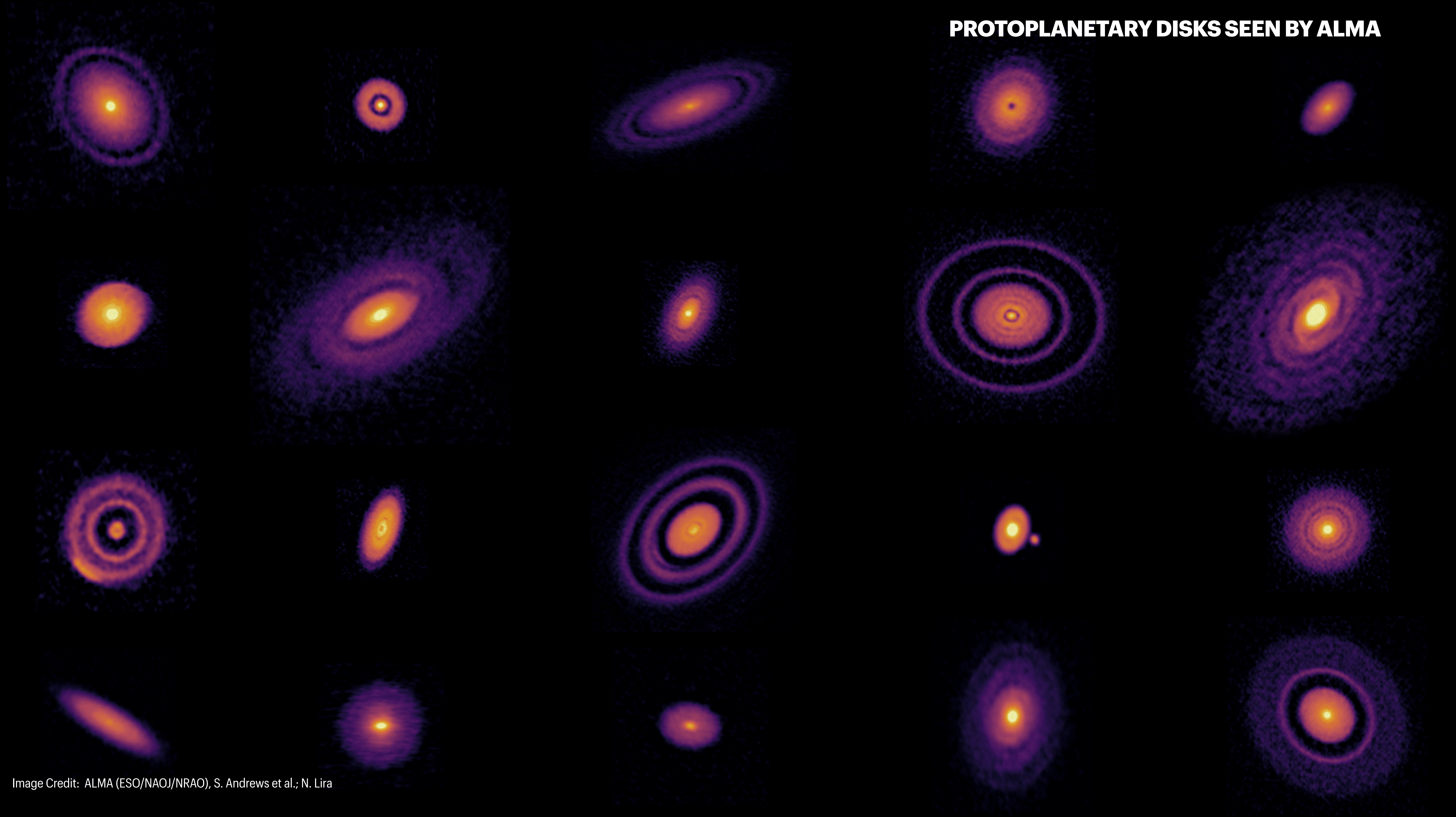


Image Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; N. Lira