Reading: OpenStax, Chapter 21, Sections 21.3 and 21.5

NOTE: The Oct 13 and 15th lectures will be delivered synchronously (while still being recorded for anyone who cannot attend) — *we will talk about black holes!!!*

EXAM #2: Wednesday, October 21 in recitation.

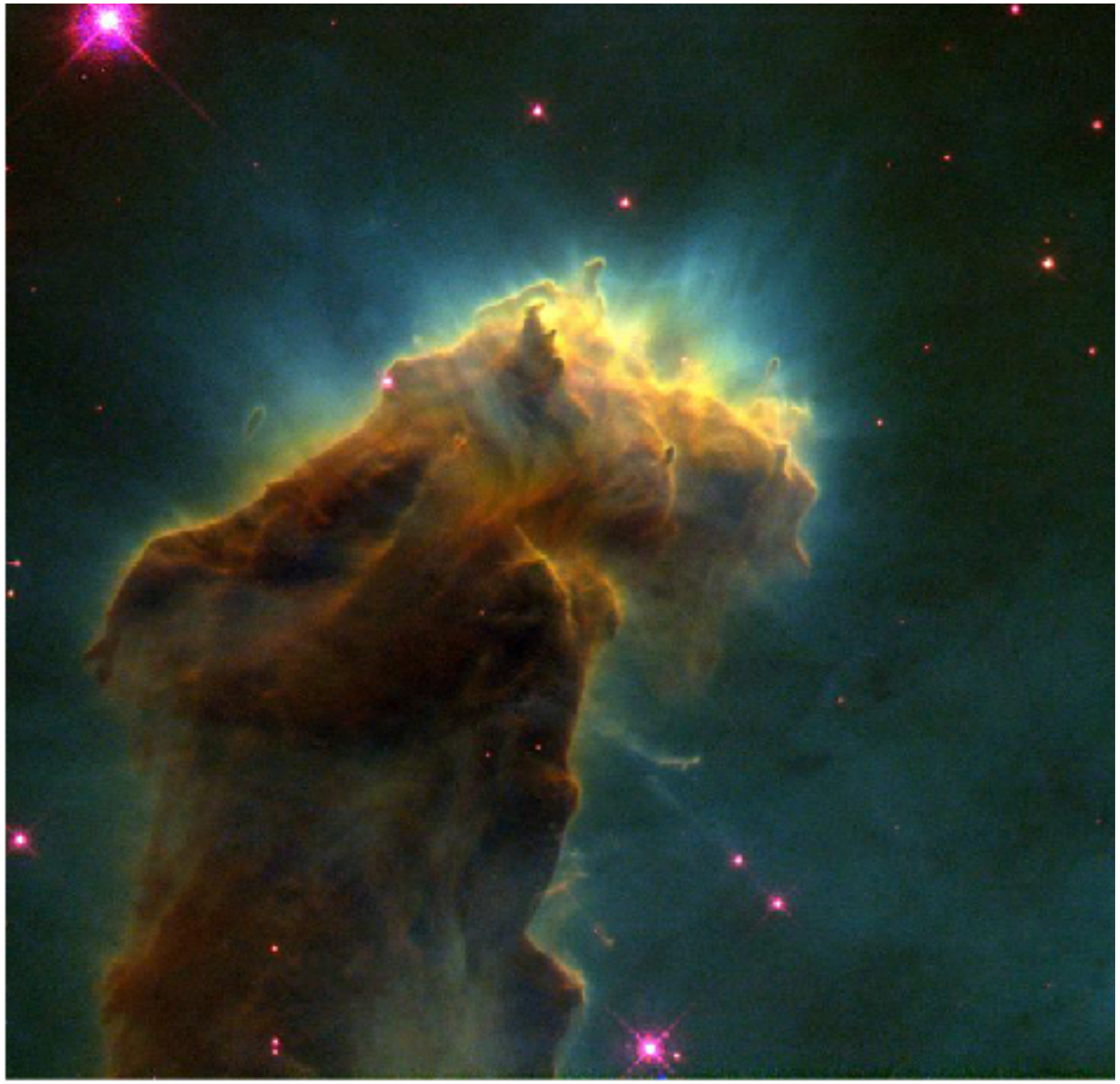
Previously: **Star Formation I: the Interstellar Medium and Cloud Collapse**

- The interstellar medium is not uniform; different types of gas clouds
- Dust makes up only 1% of the material but has a very large impact on what we can observe.
- Gas in giant molecular clouds collapse to form stars

Today: **Star Formation II: Clouds, disks, and planets**

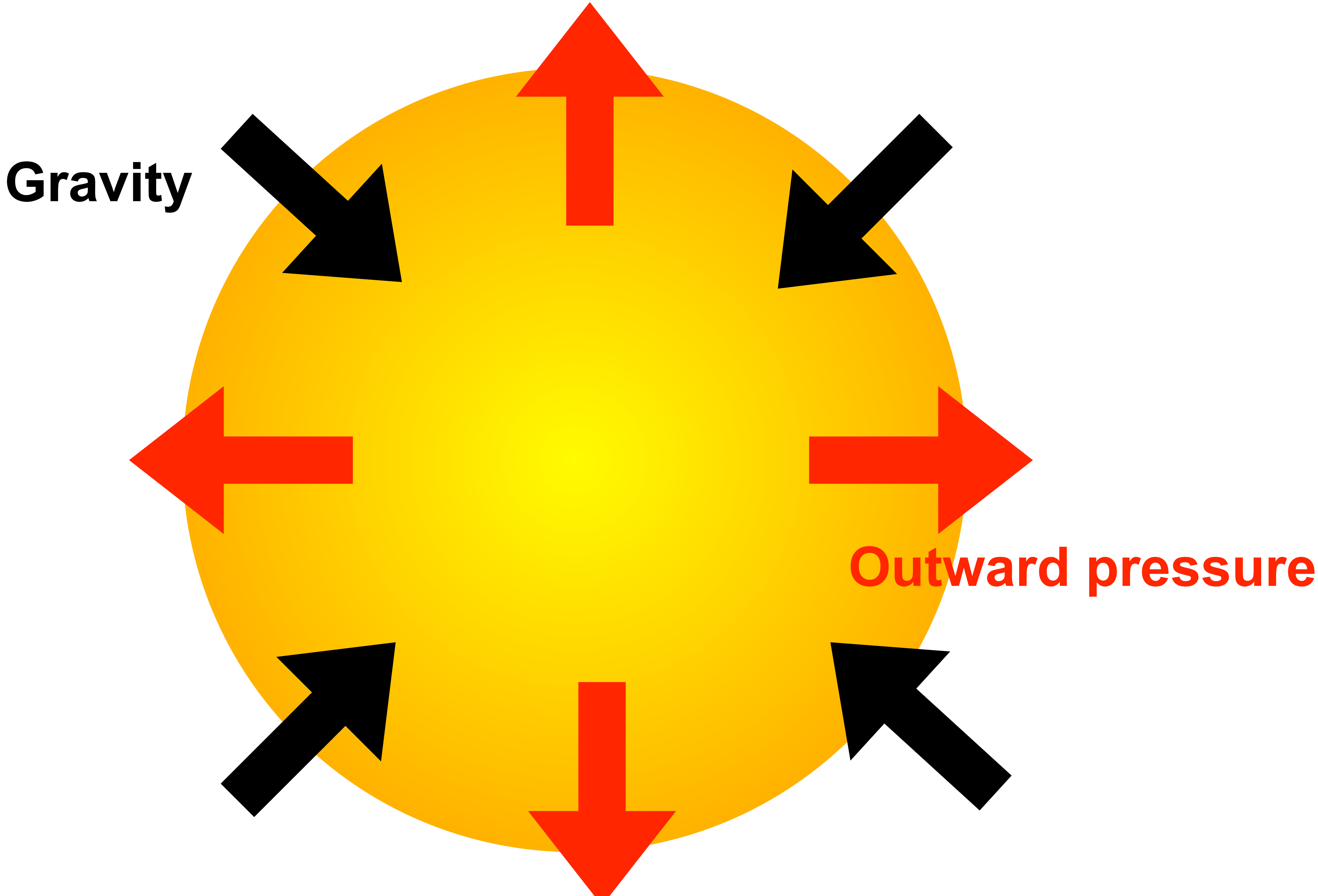
- Rotation and conservation of angular momentum leads to disks being formed around protostars
- Small dust grains within these disks grow all of the way to planets
- Nearly every star has at least one planet, and many of these exoplanet systems are different than our Solar System

Star formation



Giant molecular clouds have filamentary structures (kind of like Cirrus clouds on Earth): denser parts are called clumps and even denser parts are cores

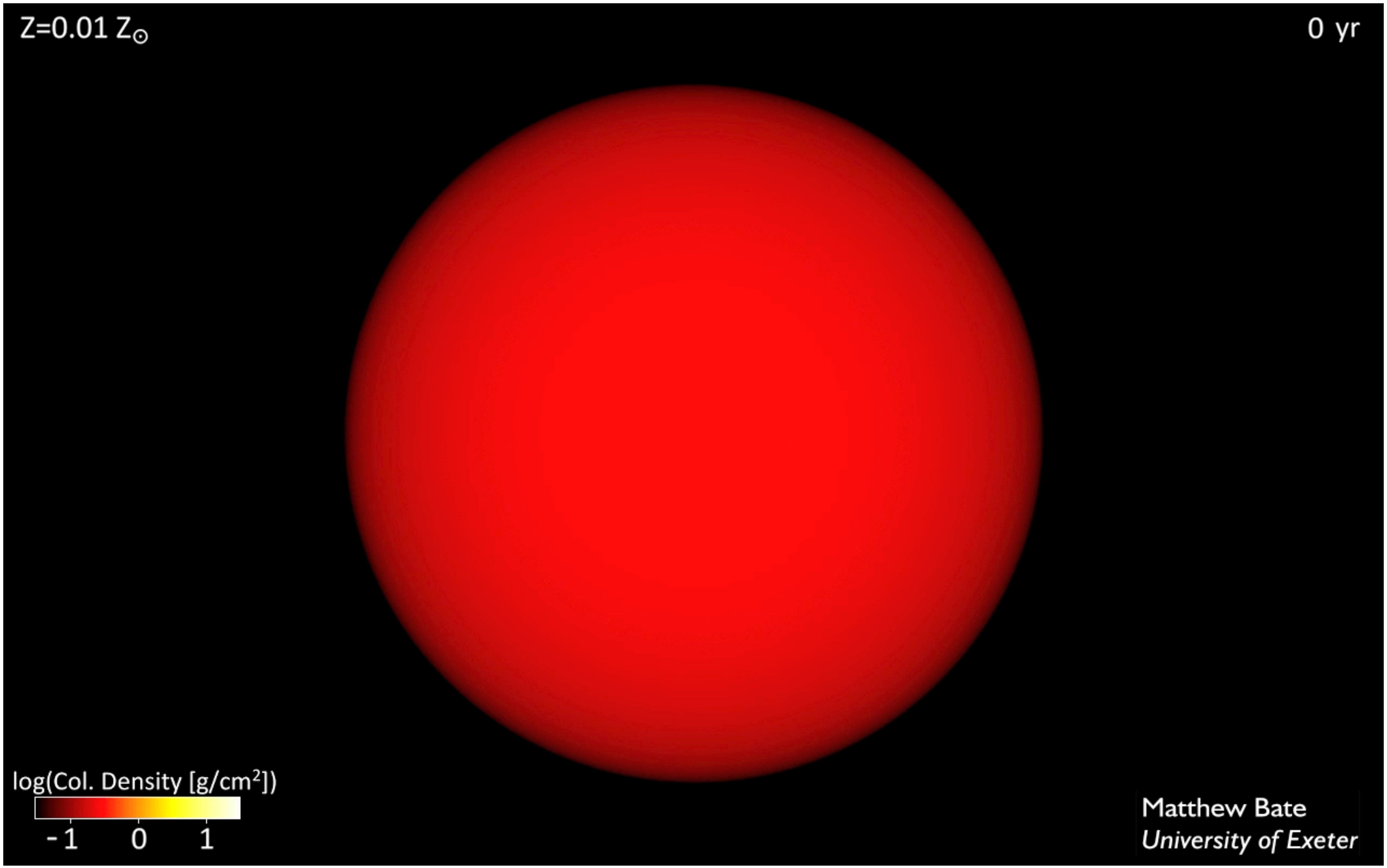
Star formation occurs within the densest regions: *cores*



Gravitational collapse

- How do you initiate the collapse?
  - **increase density** (kick the cloud)
    - **cloud collisions**
    - **stellar wind sweeping**
    - **nearby supernovae**
    - **turbulence within the cloud (like a super bumpy airplane ride)**
  - **fragmentation**
    - **initial collapse of large cloud (M>300 Msun)**
    - **density increases**
    - **smaller fragments begin their own collapse**
    - **a star cluster?**

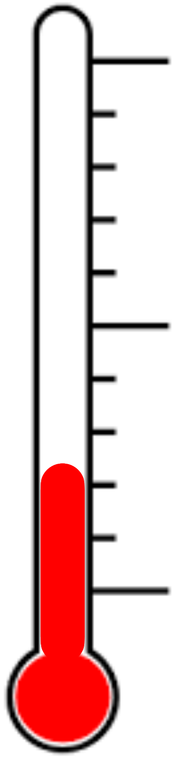
Gravitational collapse

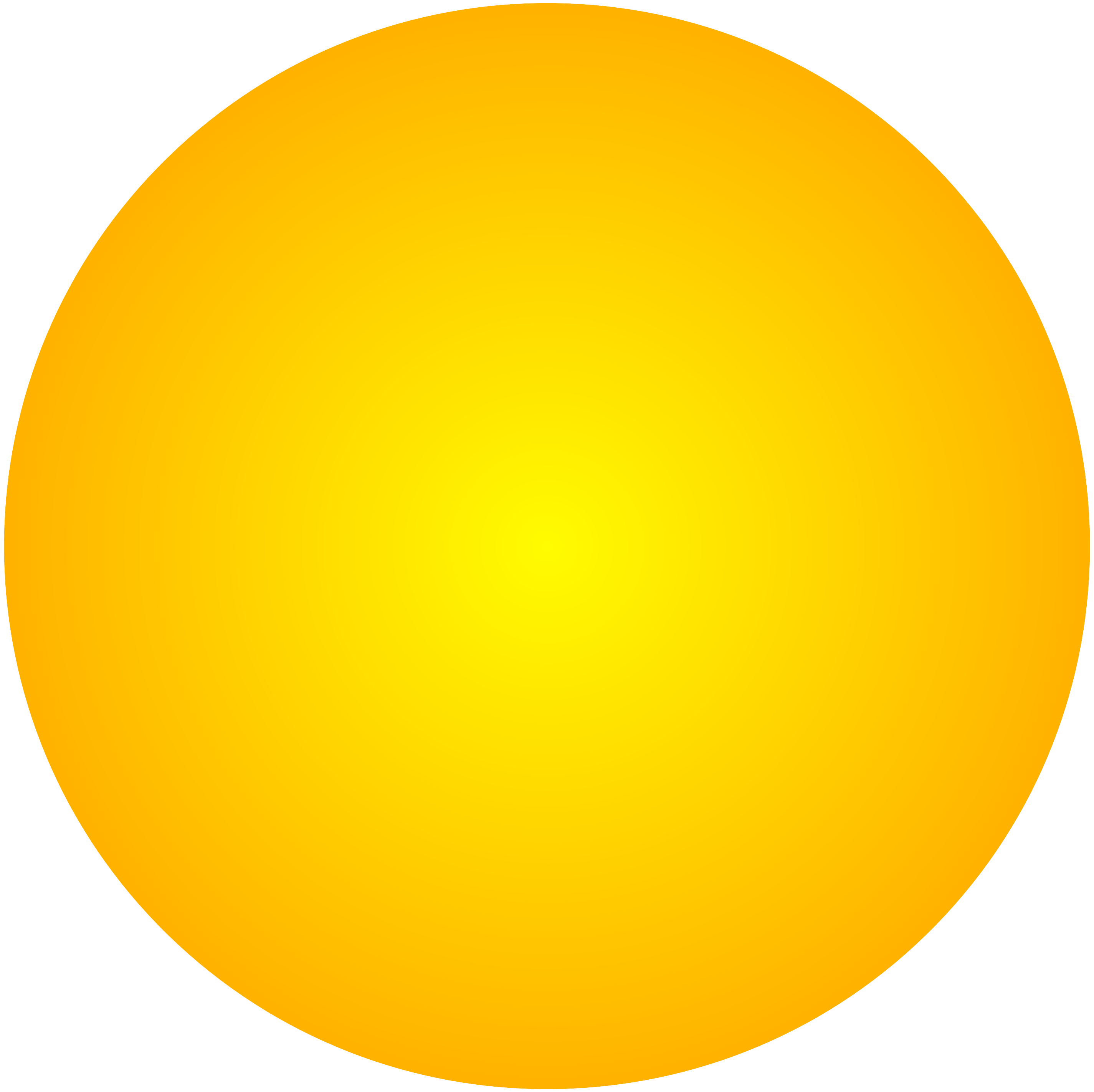


From Cloud to Star

- **Cloud Cores:**
  - Dense knots within fragments; seeds of protostars
- **The Protostar Phase**
  - initial collapse is fast (< 10^5 yr)
  - core heats up → pressure balances gravity
  - slow contraction → grav. energy (10^6) yr
- **The Pre-Main Sequence Phase**
  - larger (still) than M.S. stars
  - more luminous than M.S. stars
  - cooler than M.S. stars
  - still too cool for nuclear burning
- **10^7 yr** - core hot enough > H ignition (in pre-Sun)
- **3×10^7 years** - **1 M_{sun} star** settles onto M.S.
- **more massive stars reach M.S. faster**

Protostar shines not from nuclear fusion but from gravitational contraction!





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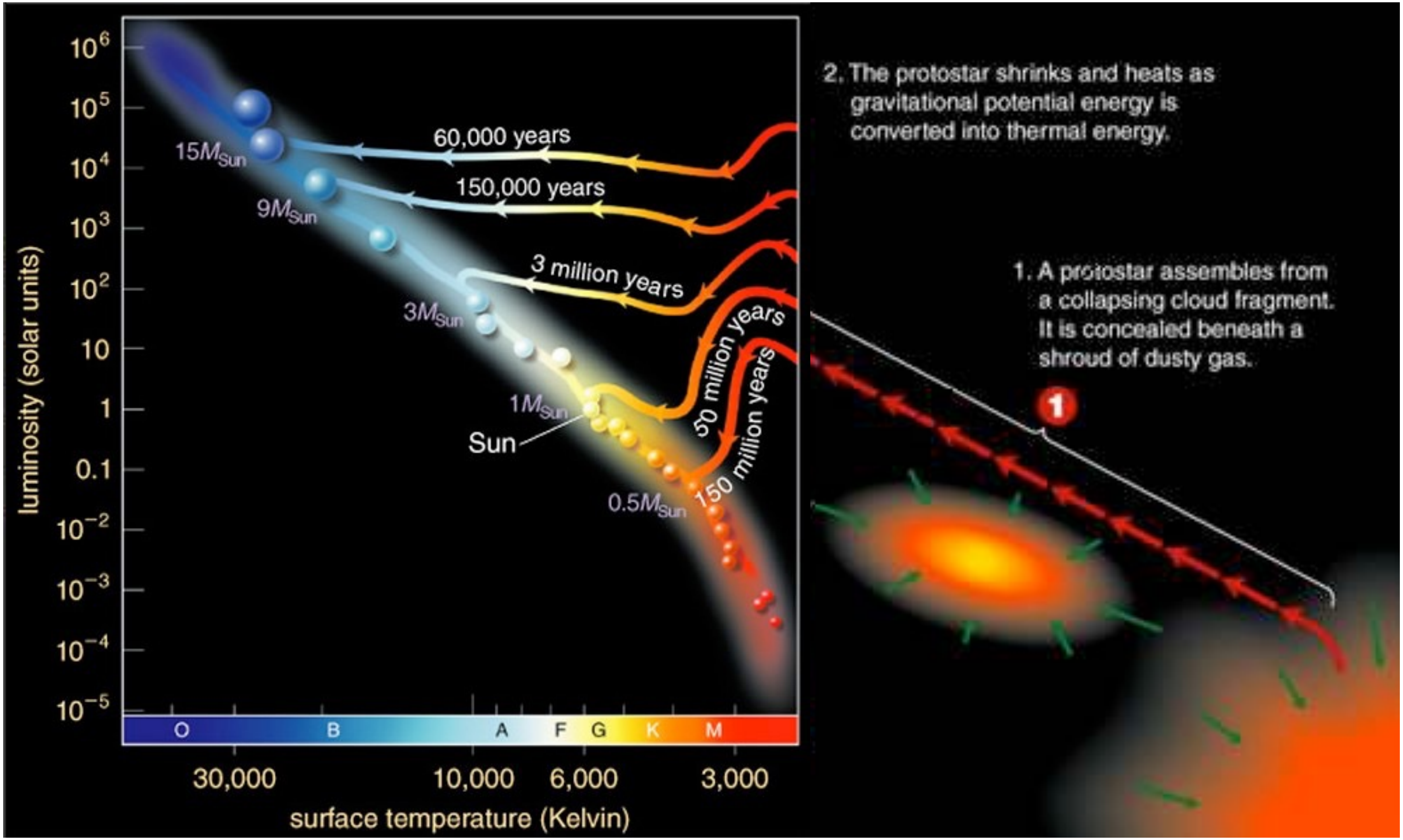
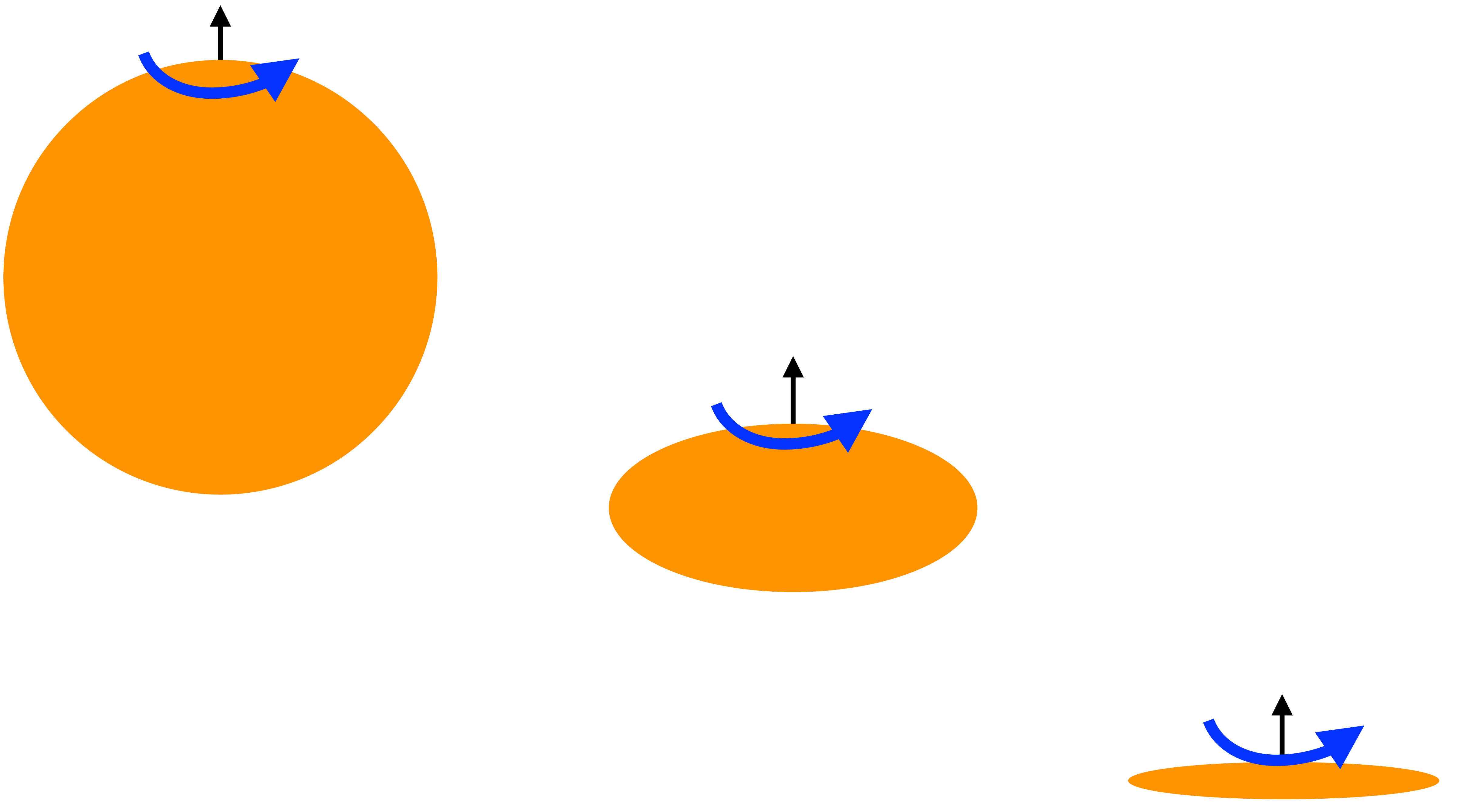
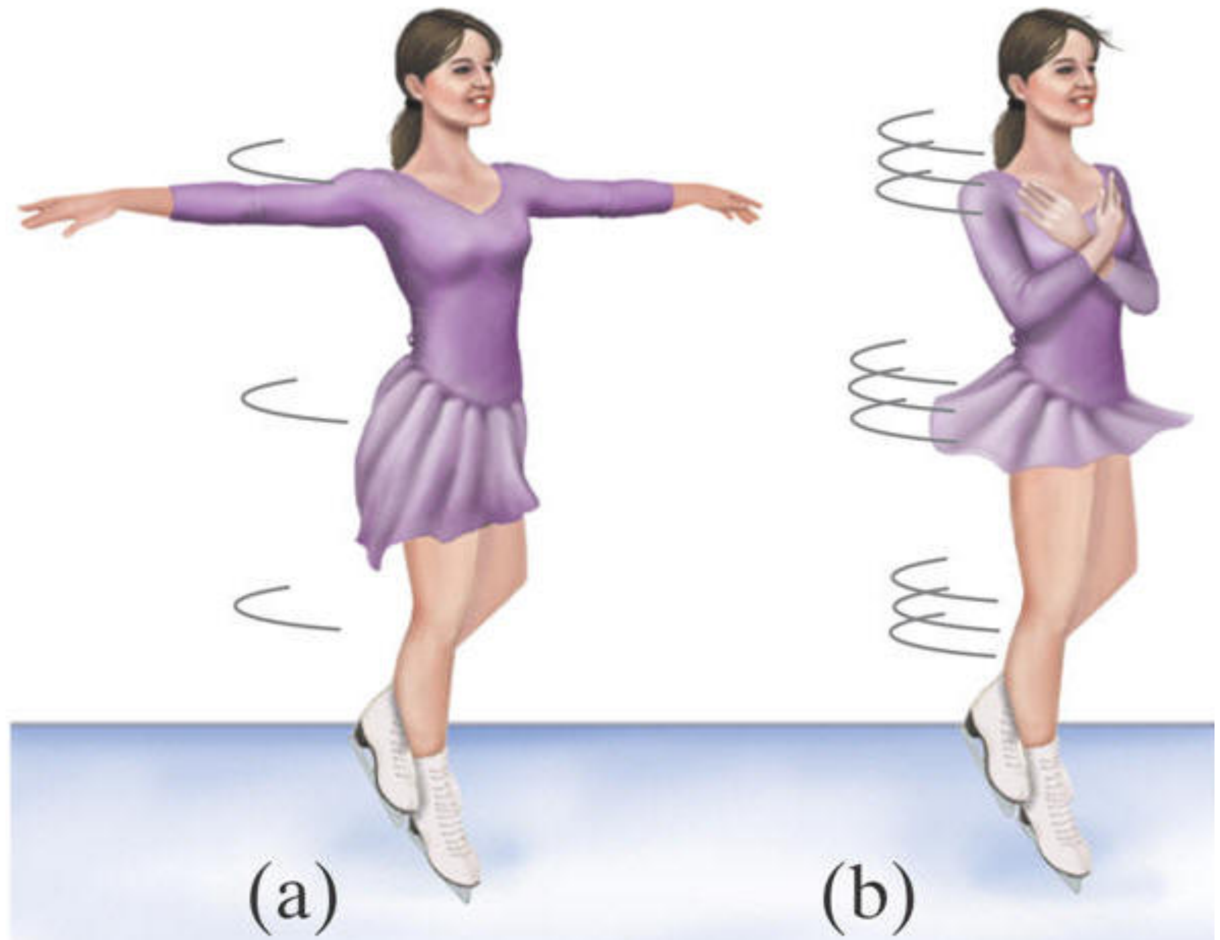


Disks form with protostars



Why does this happen?



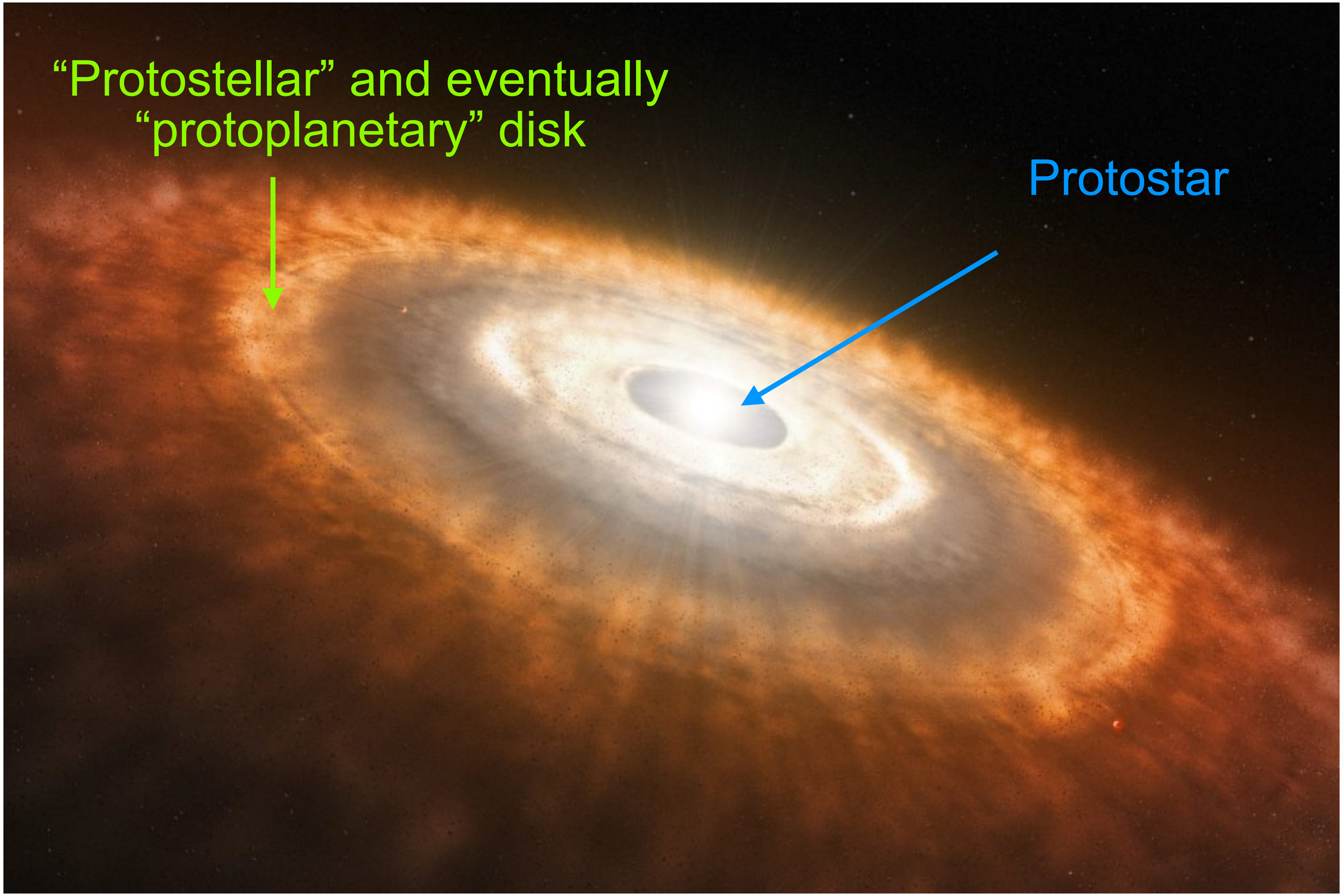
https://www.youtube.com/watch?v=VmeM0BNnGR0

So, the blob spins faster as it collapses to conserve angular momentum!

As the spin increases, material gets "flung" outward

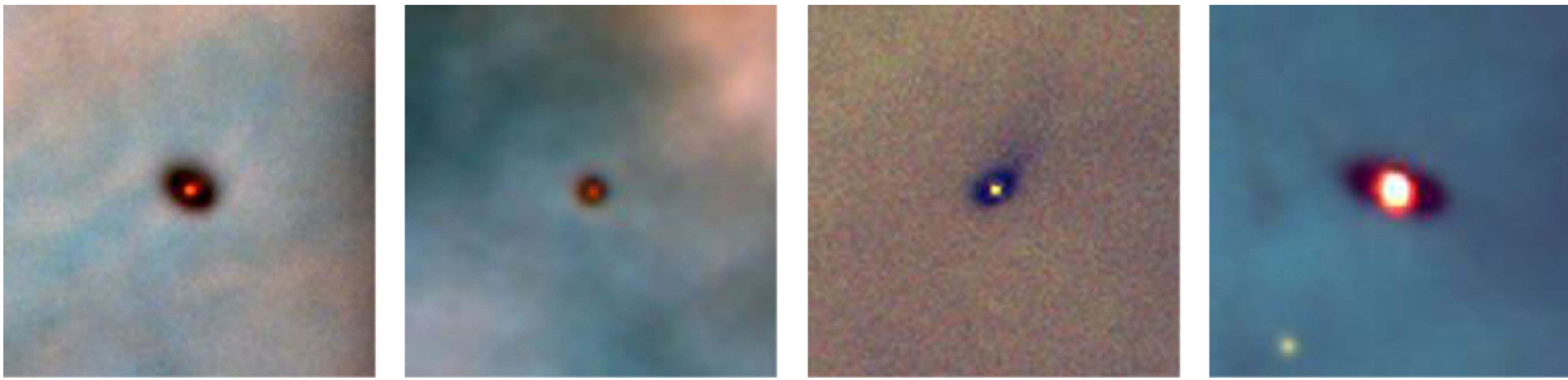
https://www.wired.com/2011/09/spinning-merry-go-round-of-death/

Some material is flung outward and forms a disk



L. Calçada/ESO

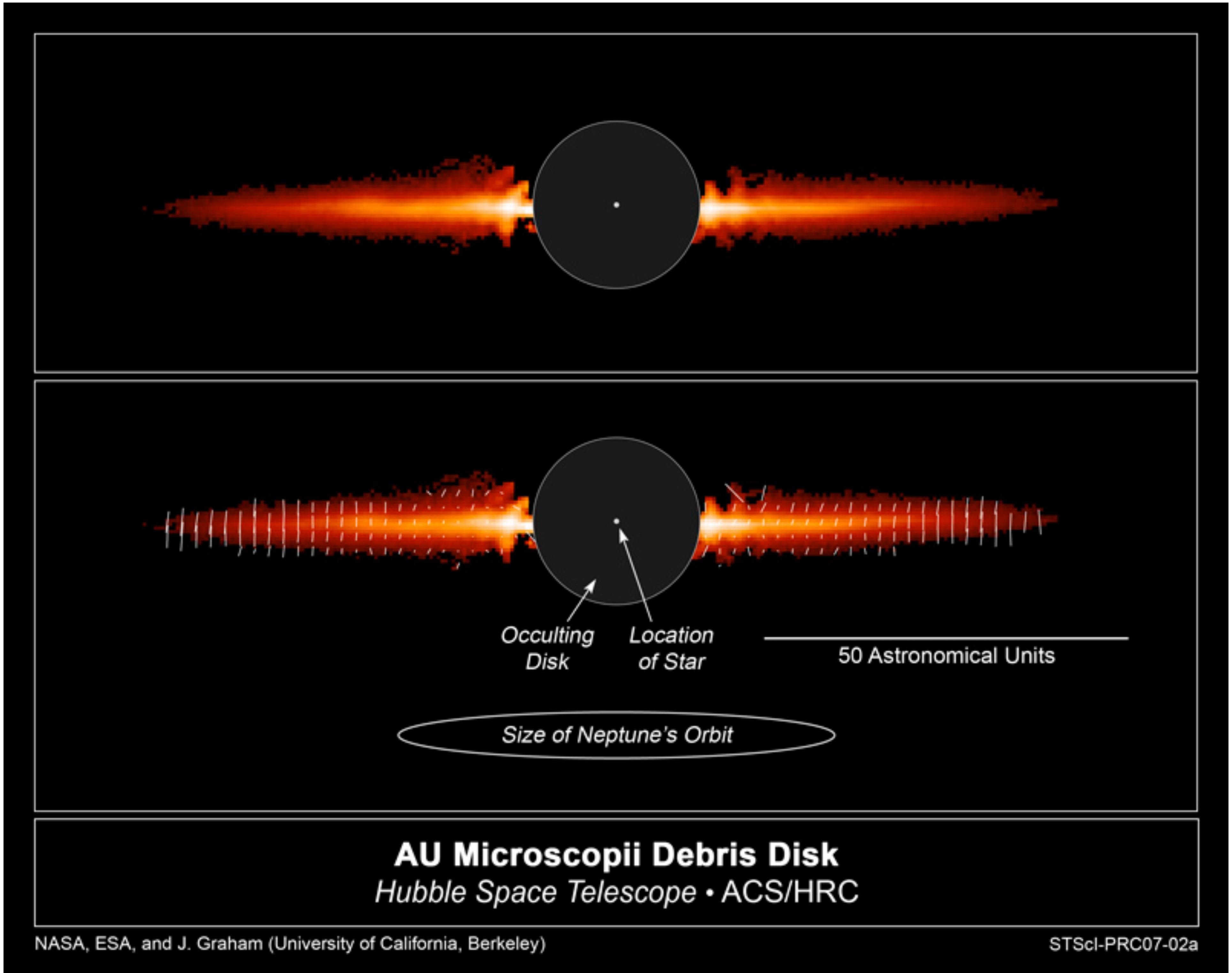
Observations of protoplanetary disks



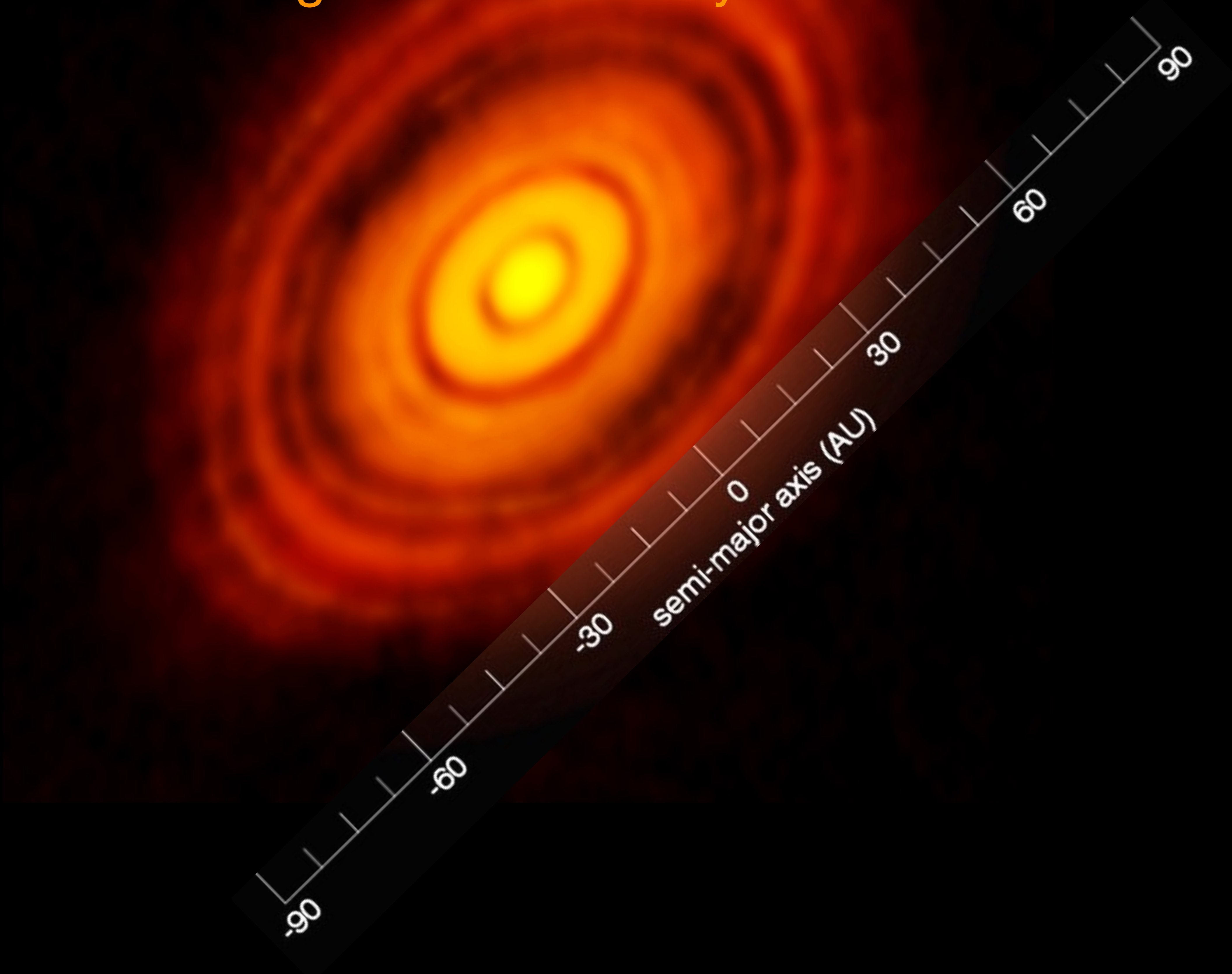
They are easiest to see by looking at the dust (infrared and mm emission!)

*But you can see them in *emission lines* too!*

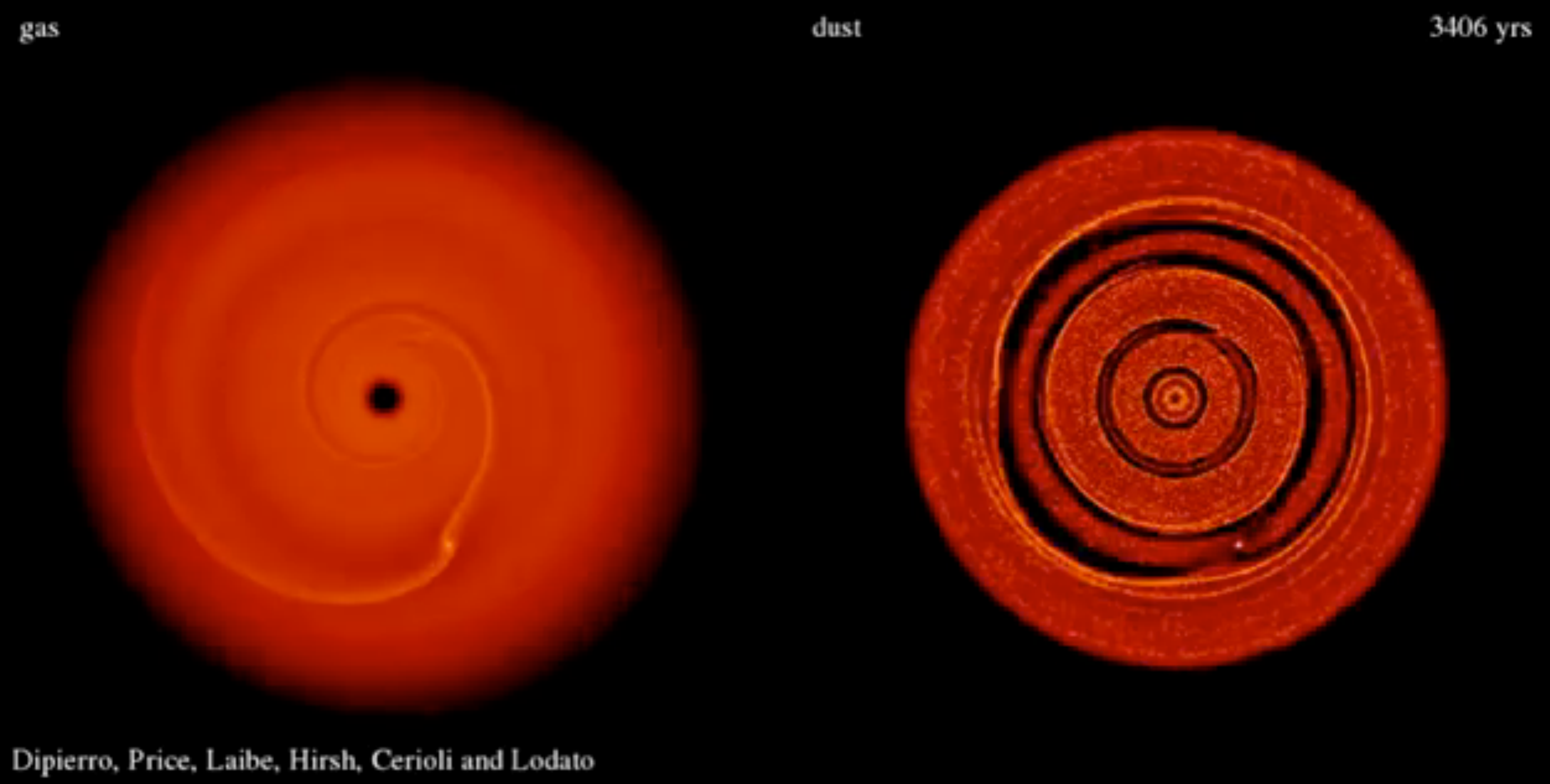
Observations of protoplanetary disks



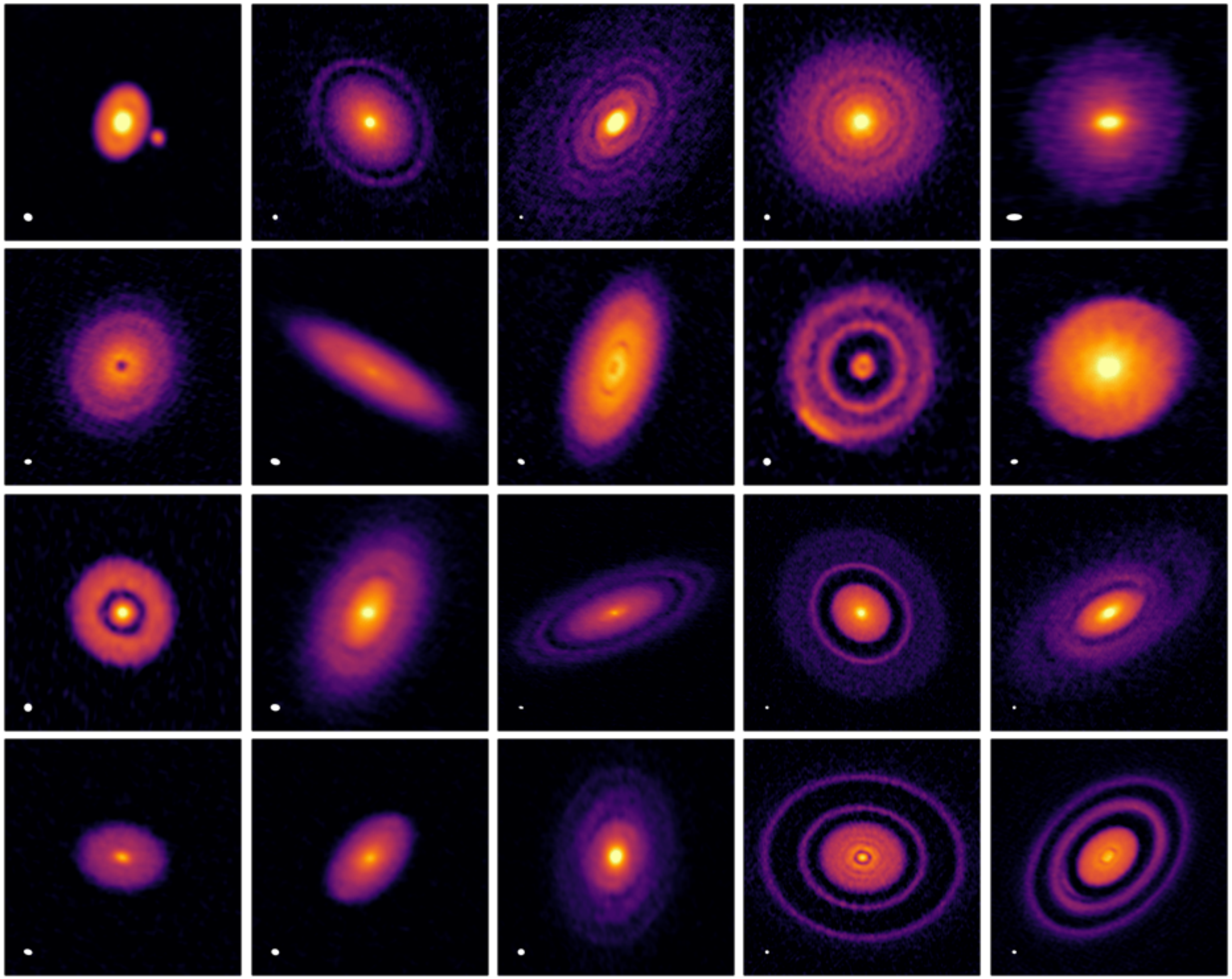
HL Tau - a planetary system in formation imaged in sub-mm by ALMA interferometer



Simulation of HL Tau

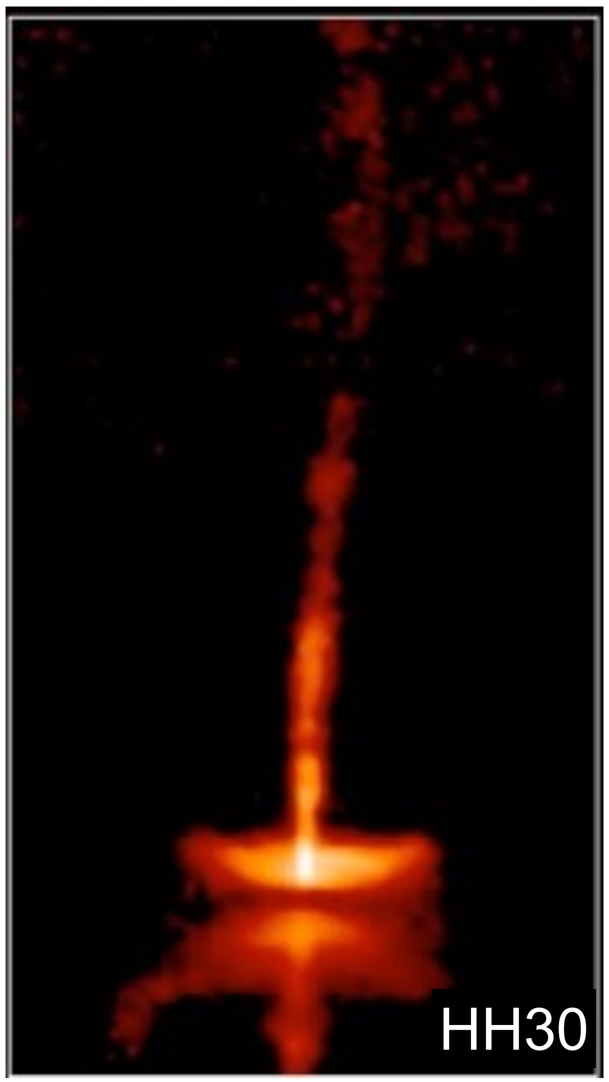


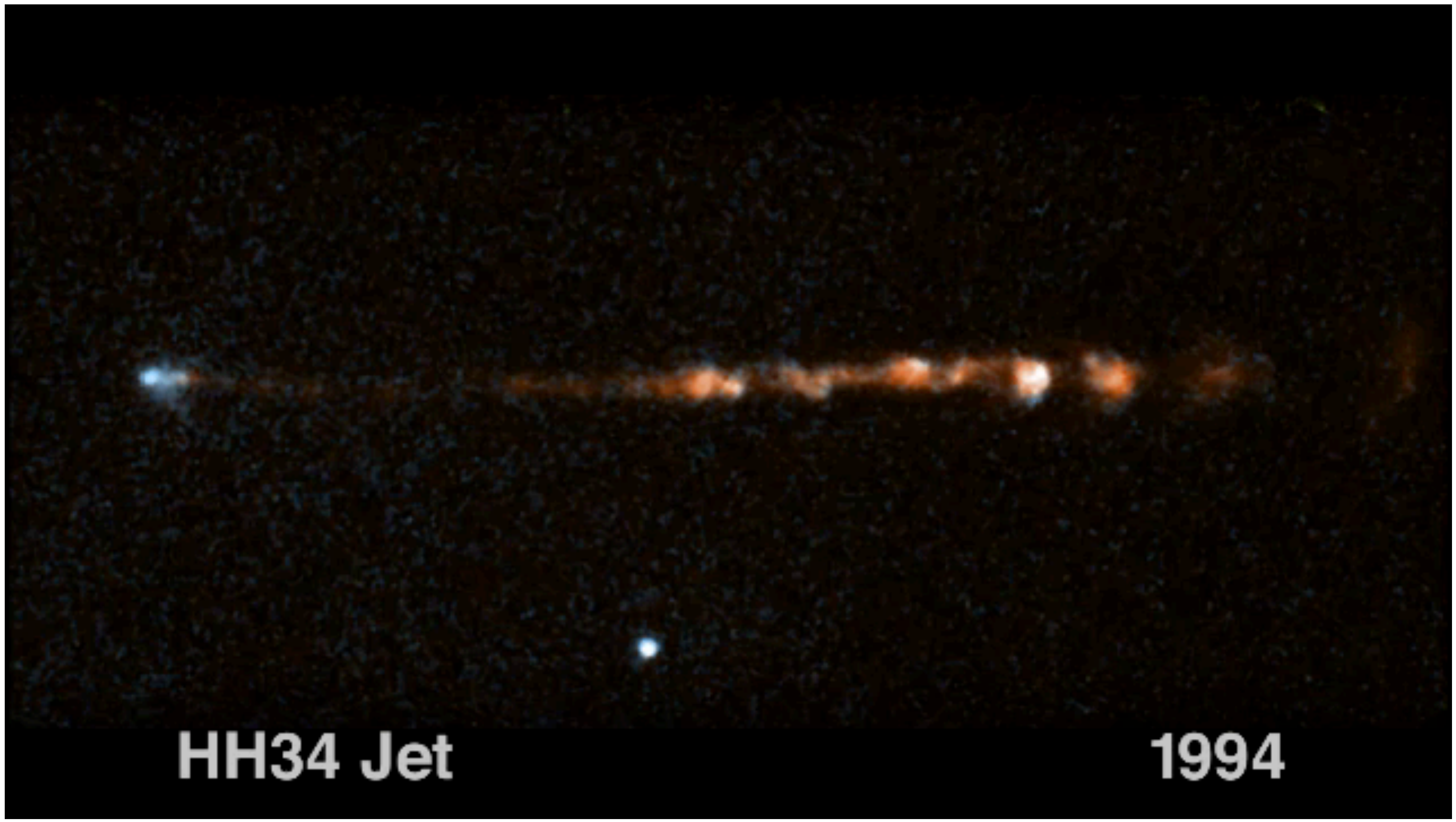
Many disks have rings



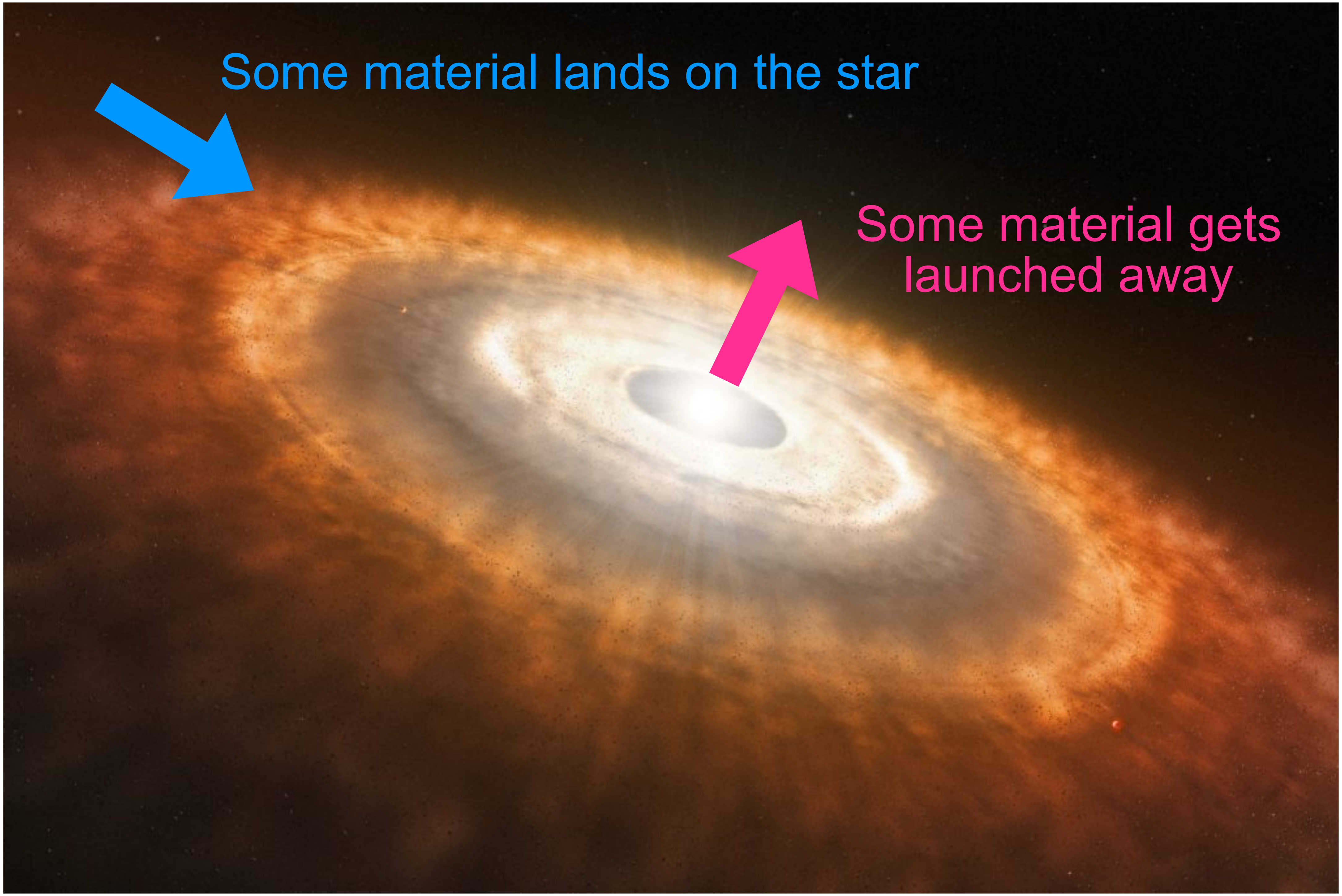
DSHARP

Often times, there are also jets





How does this work?



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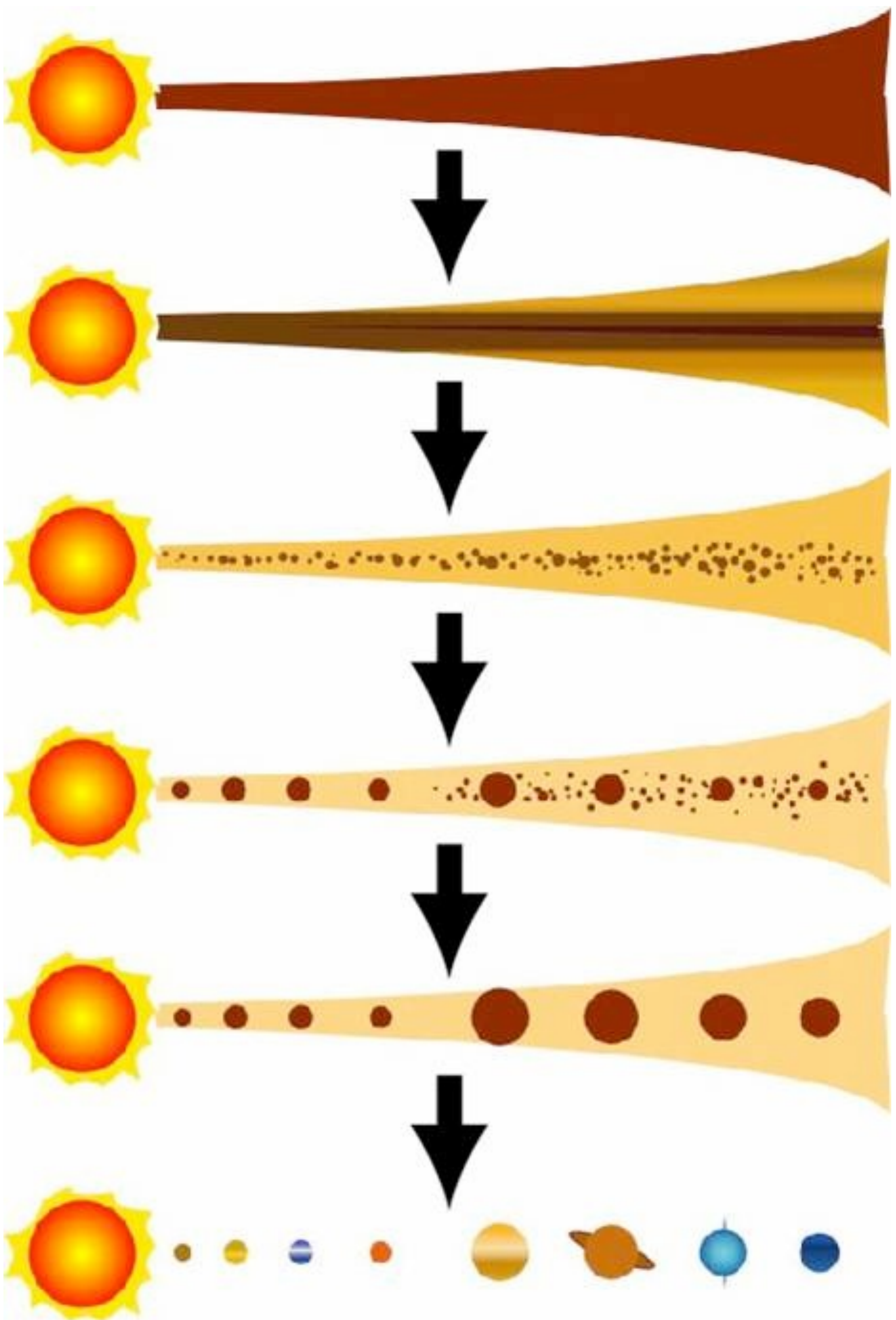
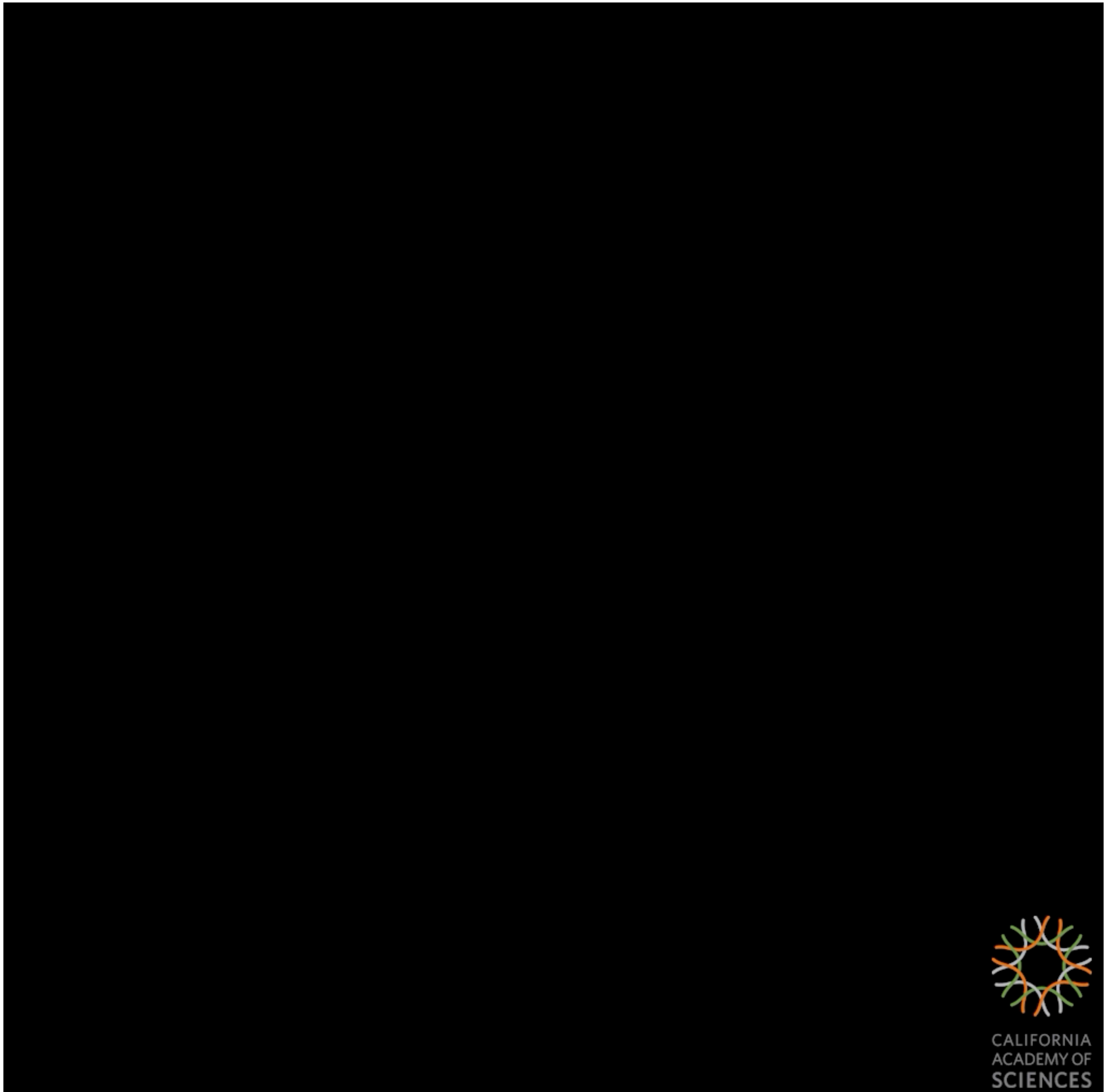
Planet formation



- Dust settles out (like a room that hasn't been dusted for awhile)
- Dust starts to grow to larger and larger particles (like dust bunnies in your corner). Eventually, this doesn't work anymore
- Eventually "planetesimals" form (these are small planet-like bodies, e.g., asteroids) through gravity
- Planetesimals either sweep up the remaining dust particles or merge together to form planets

Planetesimal formation



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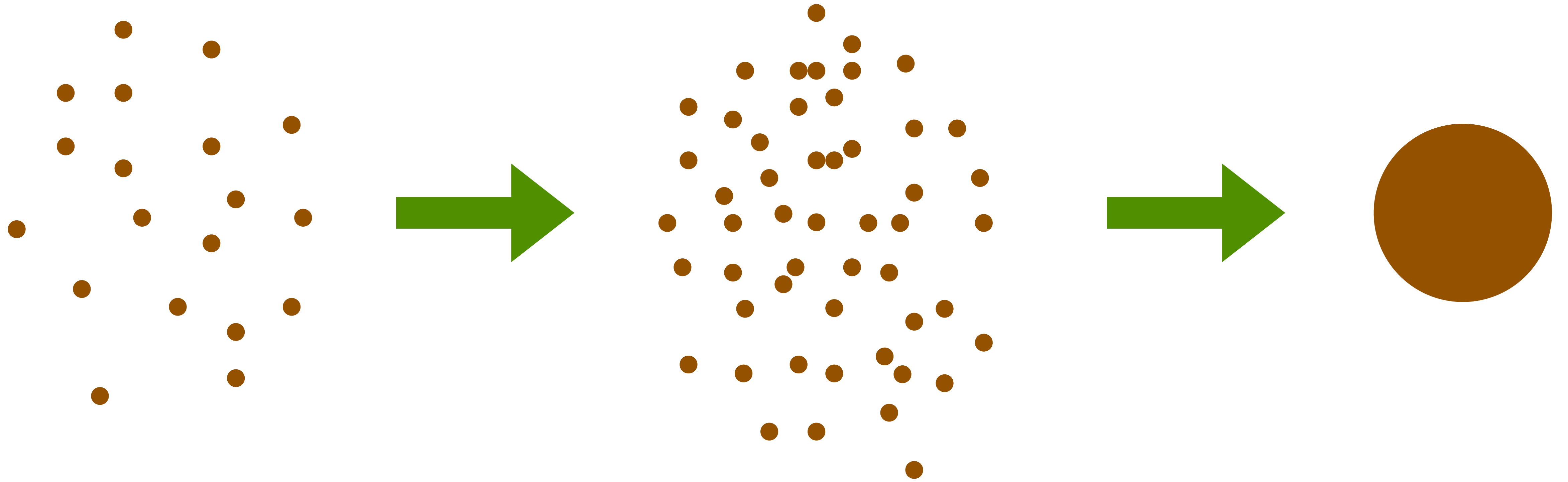


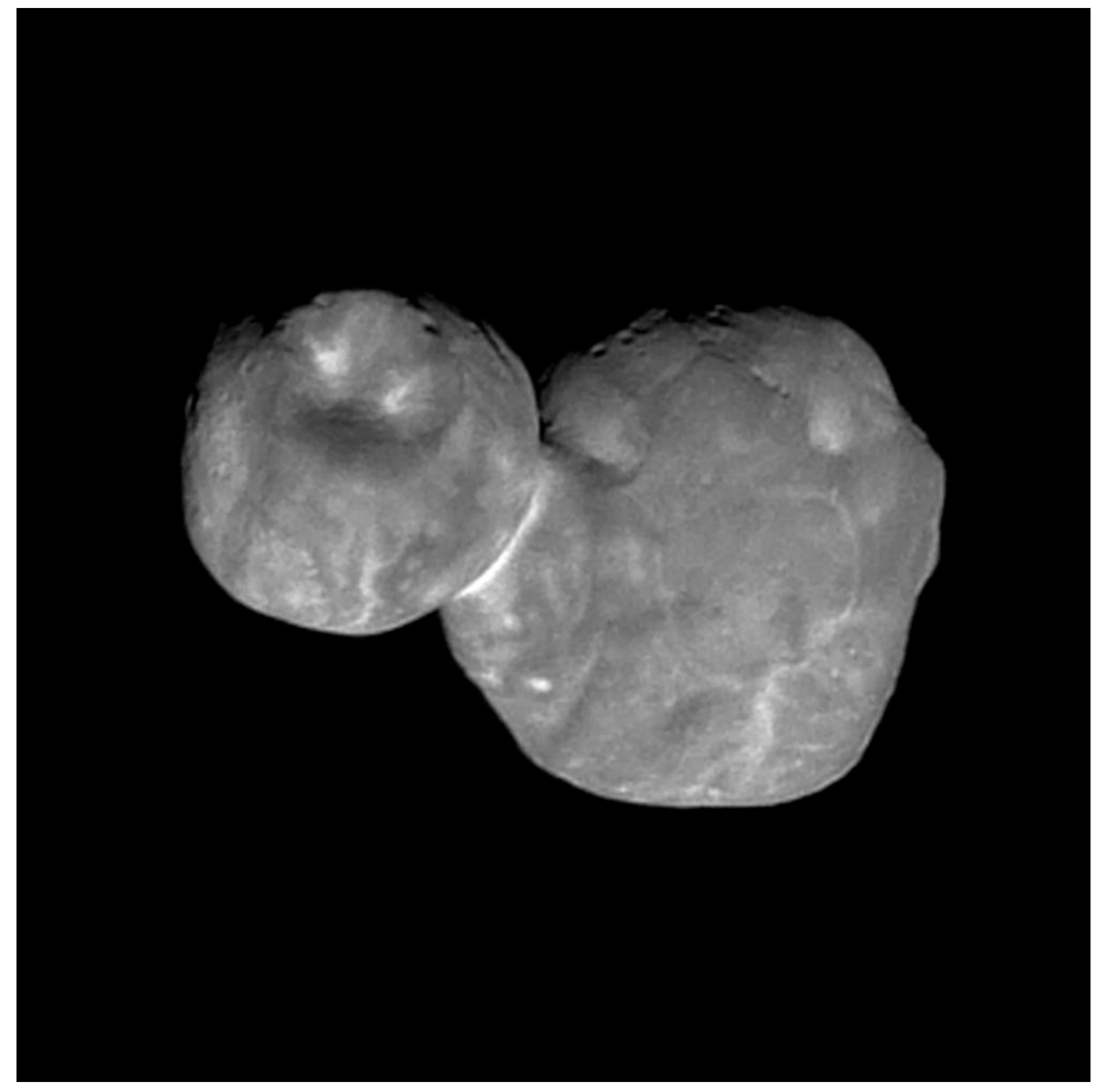
Swarming of small particles (~cm in size)

Swarming continues and grows!

Eventually gravity takes over and a planetesimal is born!

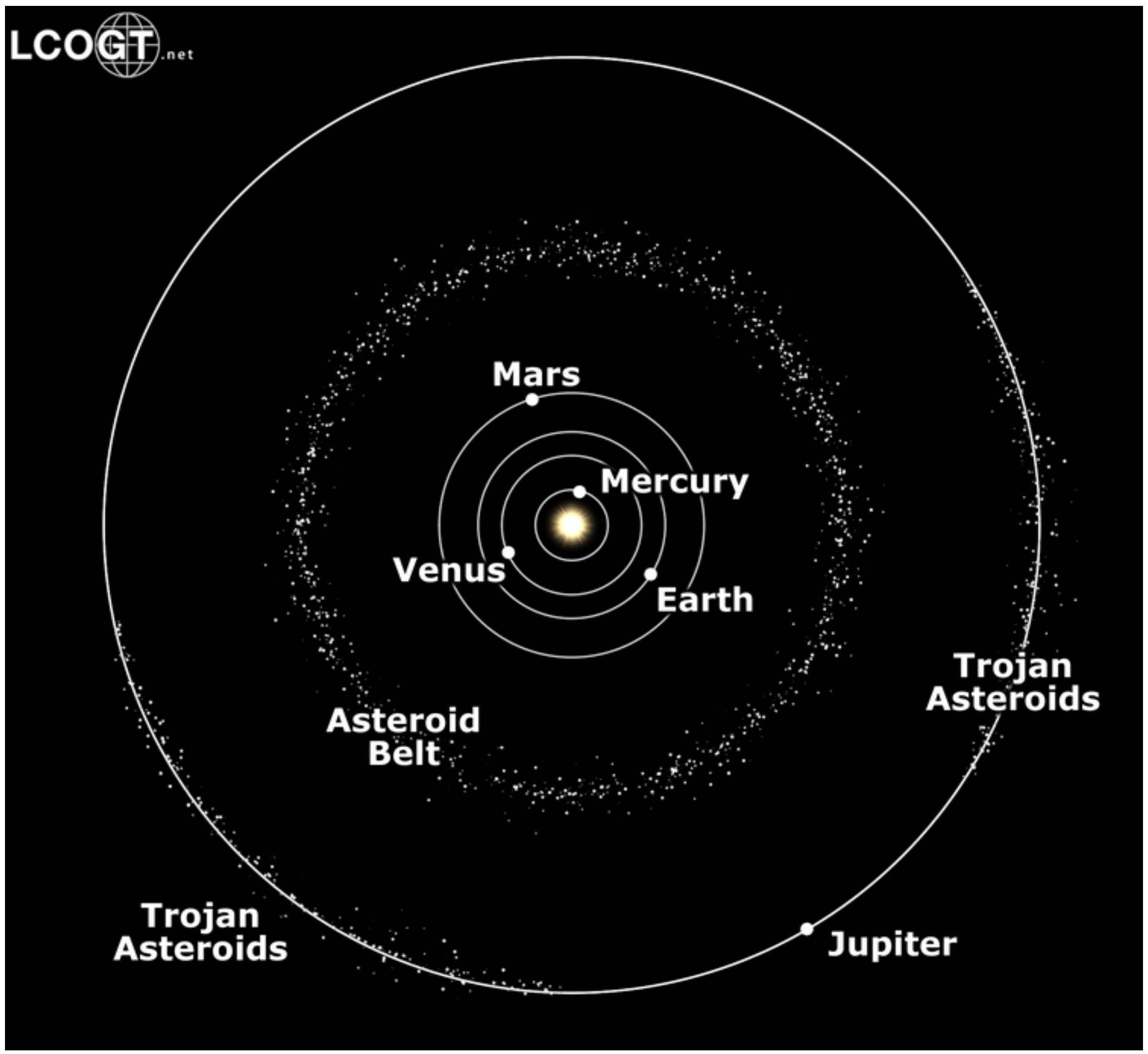
Planetesimals

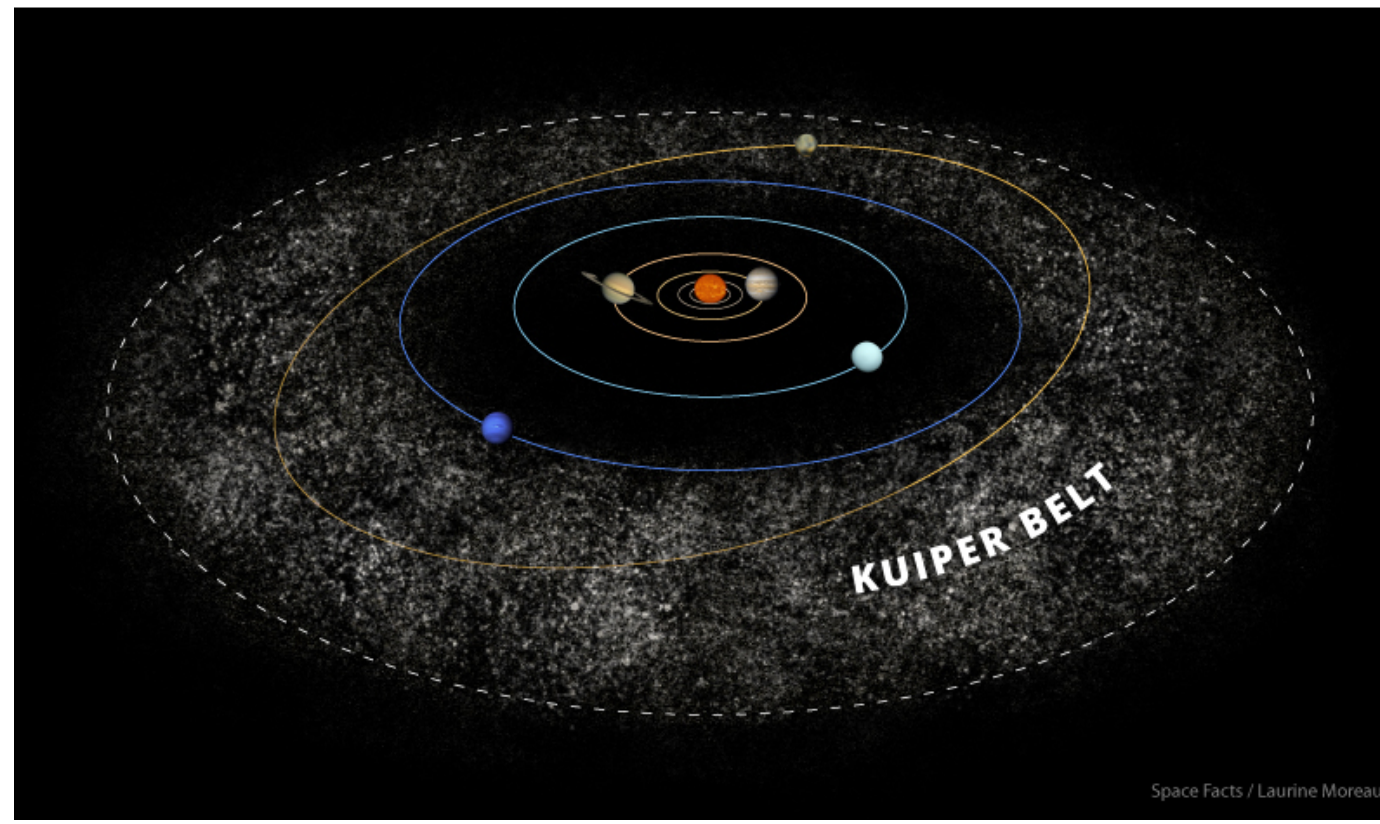
Rosetta



MU69 (aka Arrokoth), credit: NASA/JHU APL/SwRI

Planetesimals





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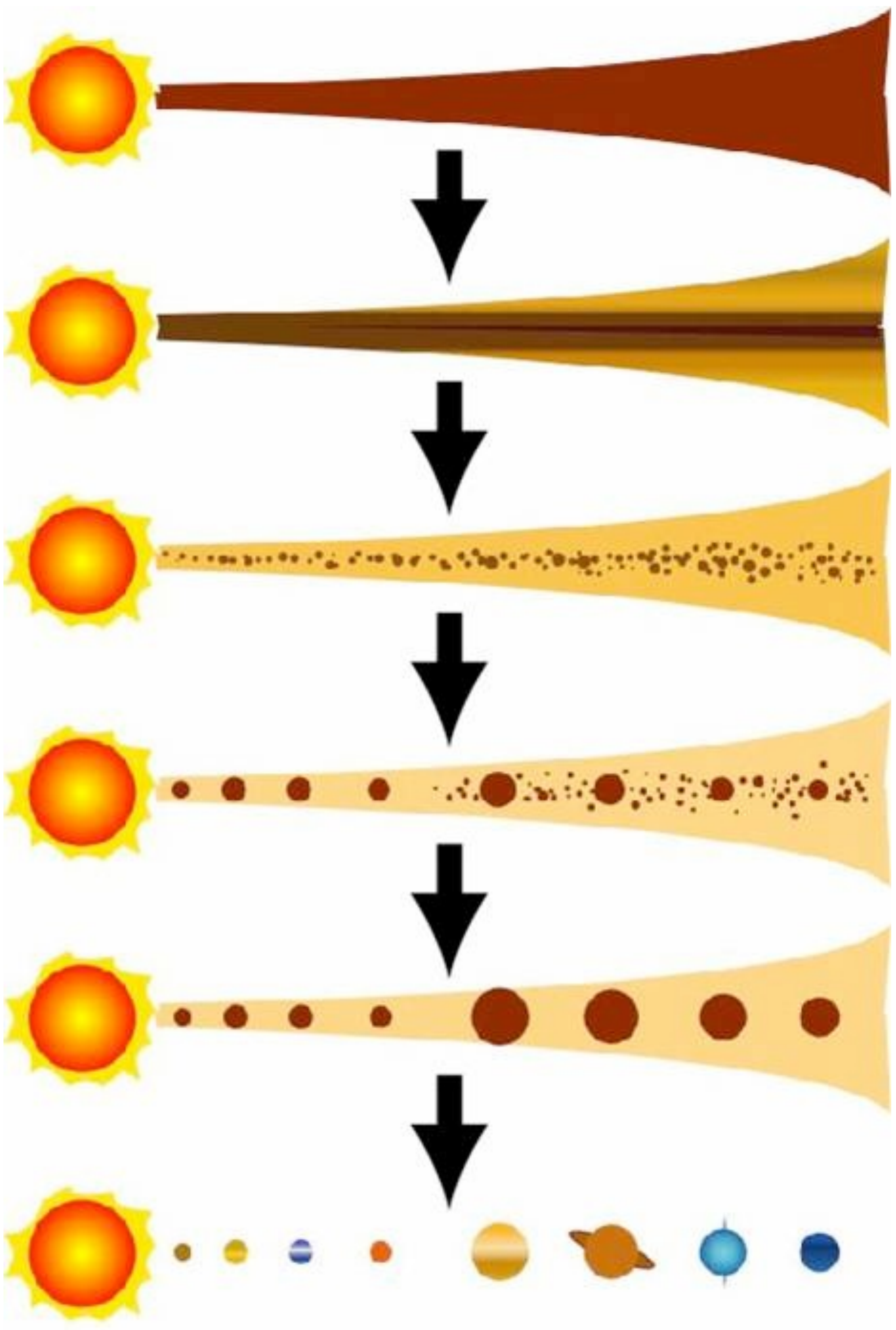

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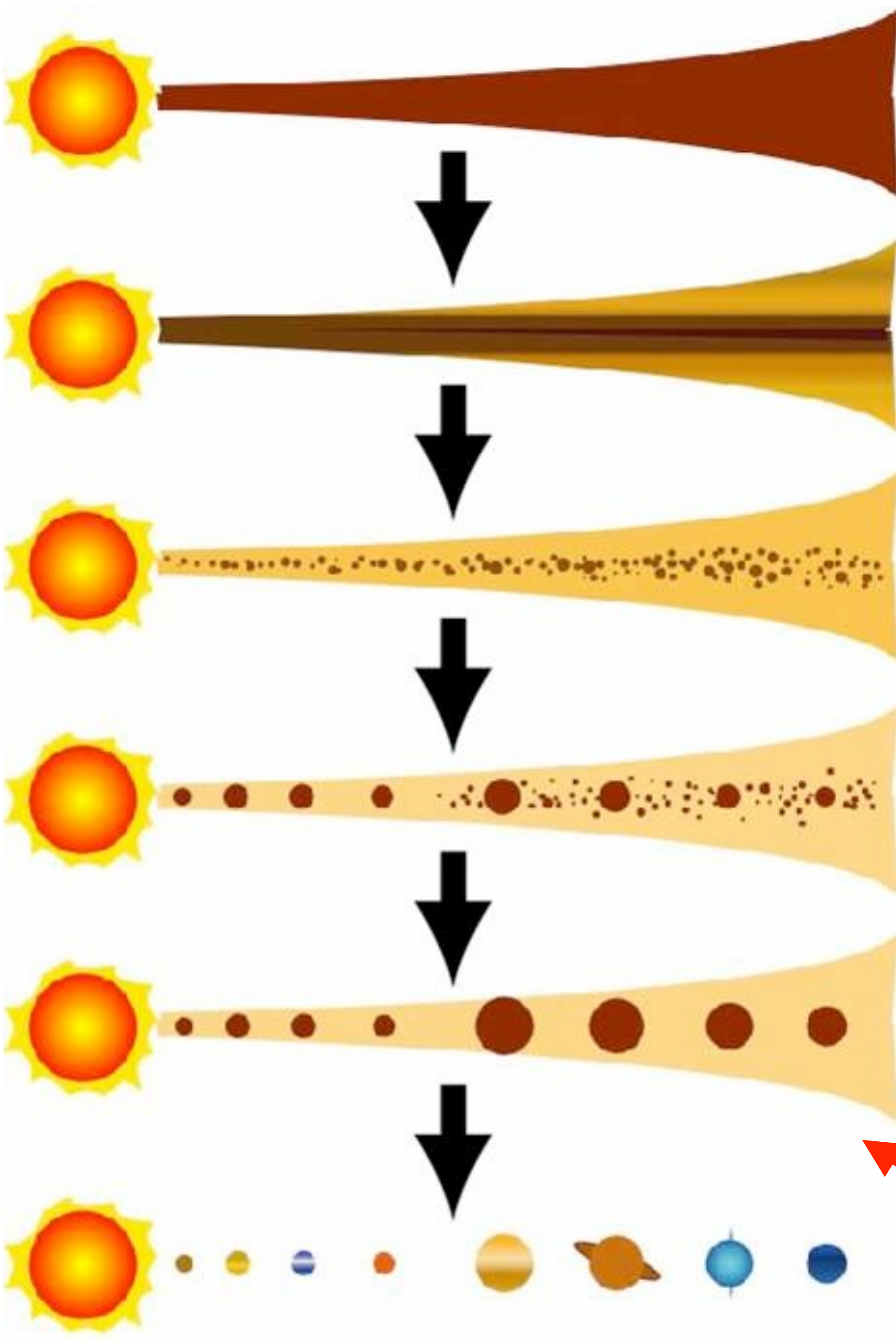
Planet formation



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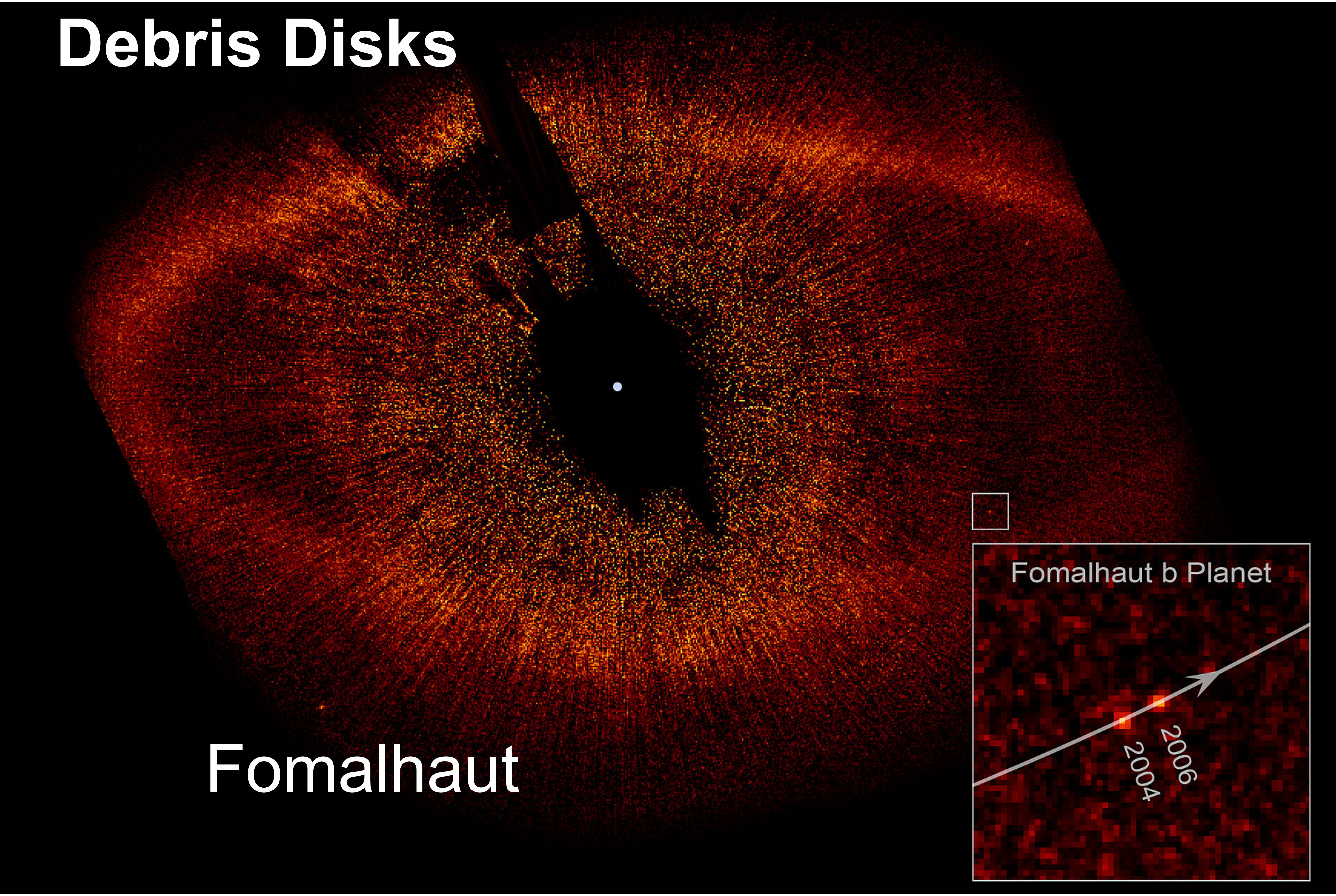
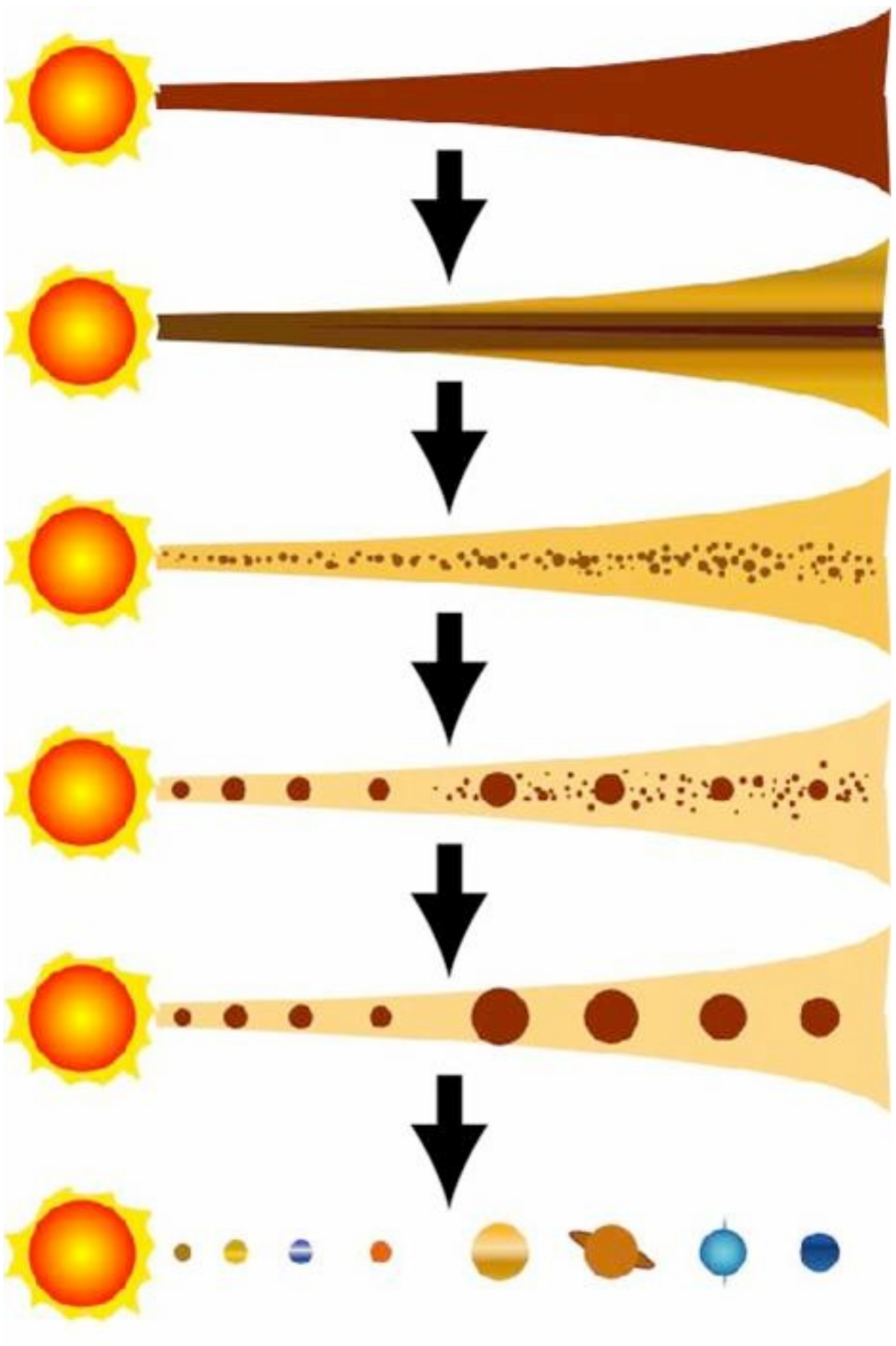
Also, radiation (and other effects) blow away the remaining gas!

Debris Disks



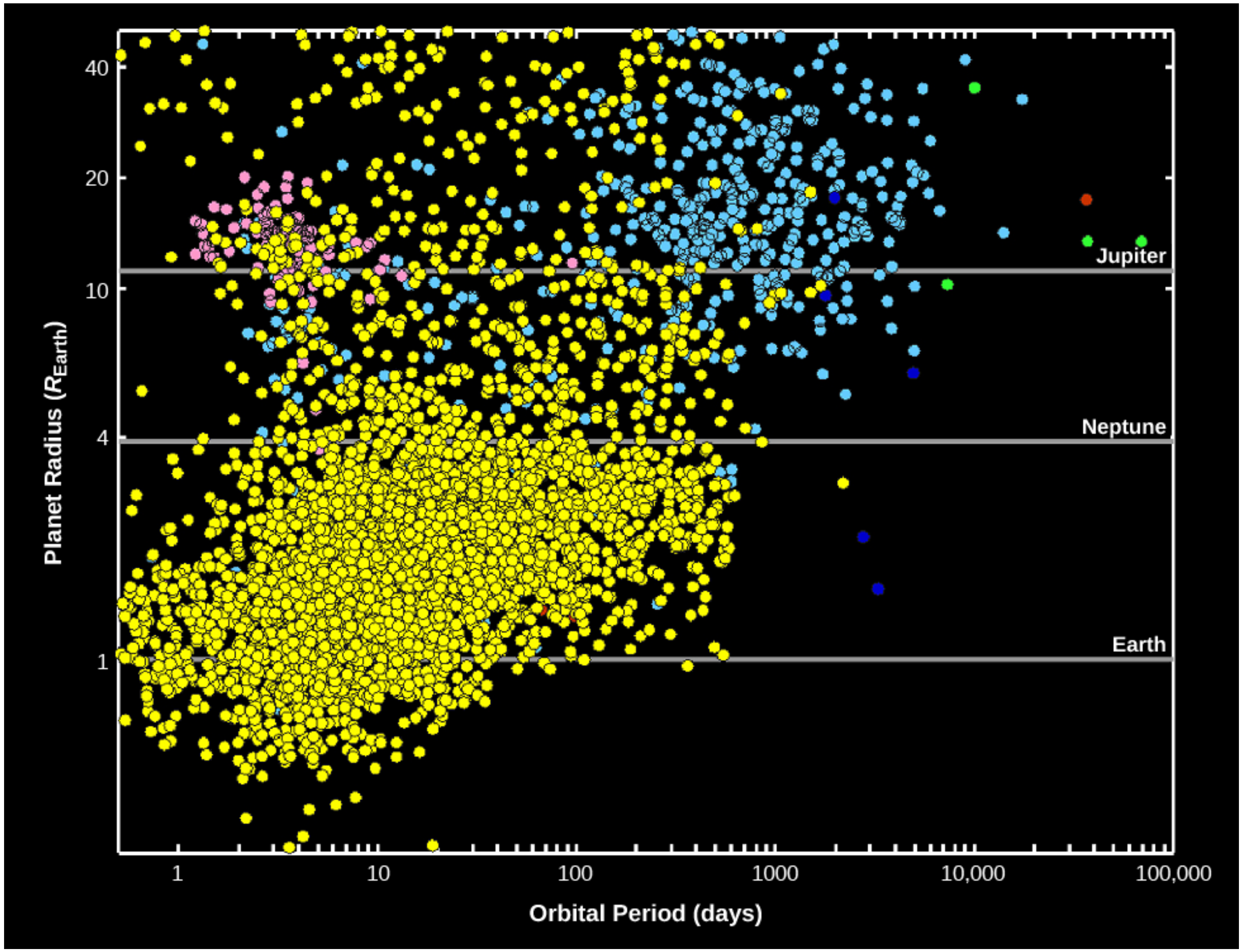
NASA

Planet formation



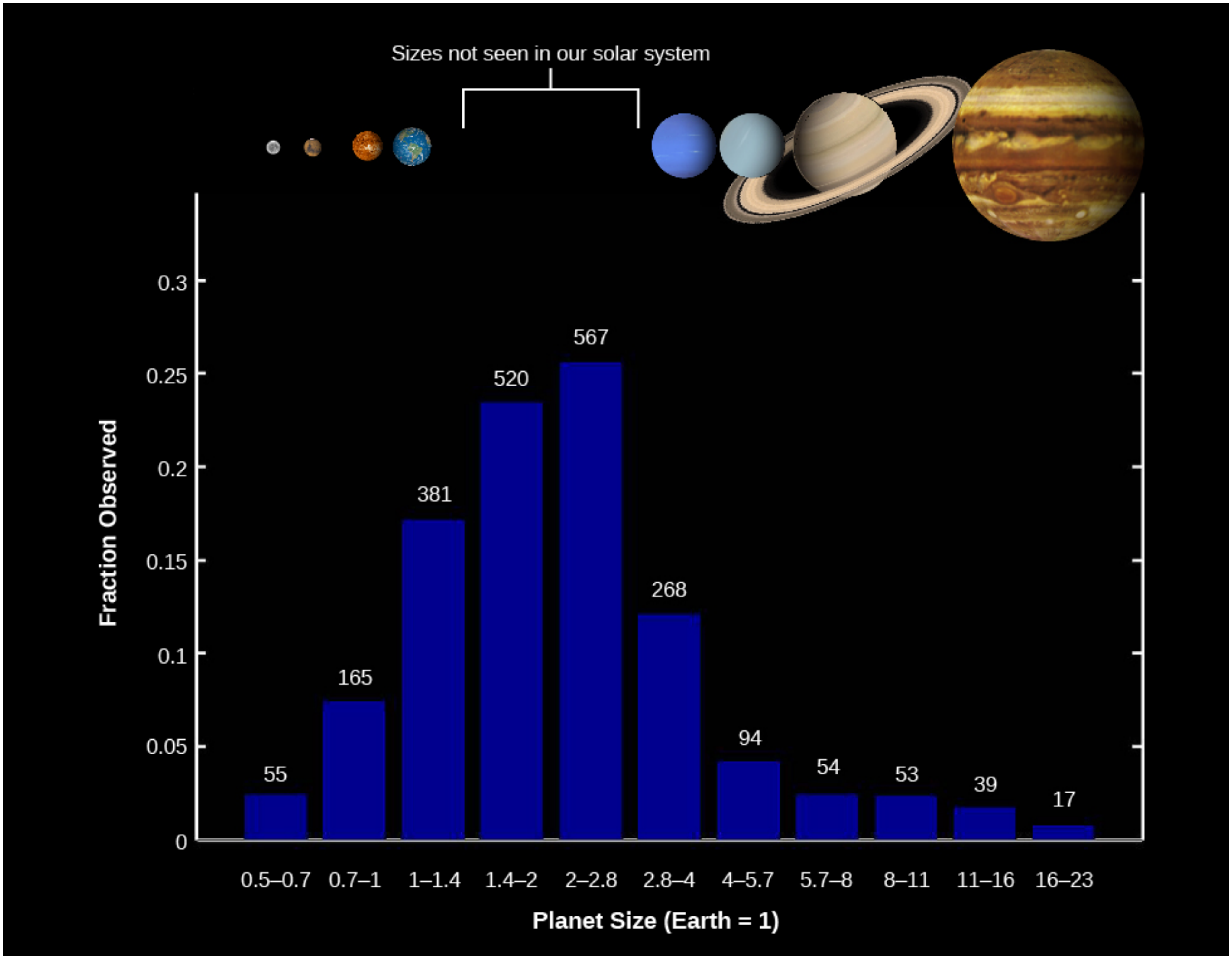
All of this happens in < 100 million years after initial collapse!!!

Exoplanets

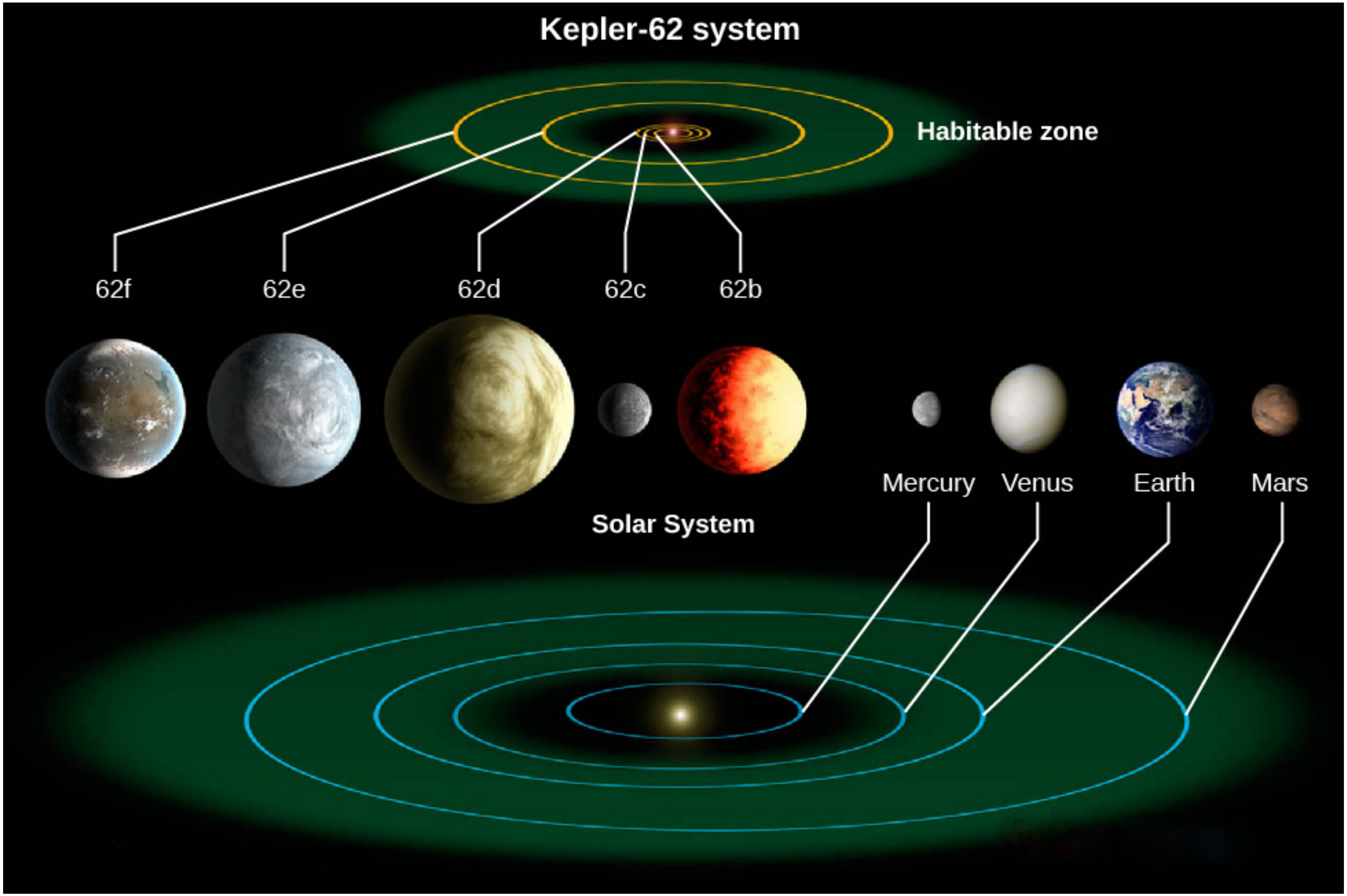


- Almost every star in the Milky Way (and probably in the Universe) has at least one planet!
- Most are between Earth and Neptune in size
- Some are as large as Jupiter or larger, and some of these are *VERY* close to their star

Our Solar System is kind of an oddball



Exoplanet systems can be very compact



Summary of star and planet formation