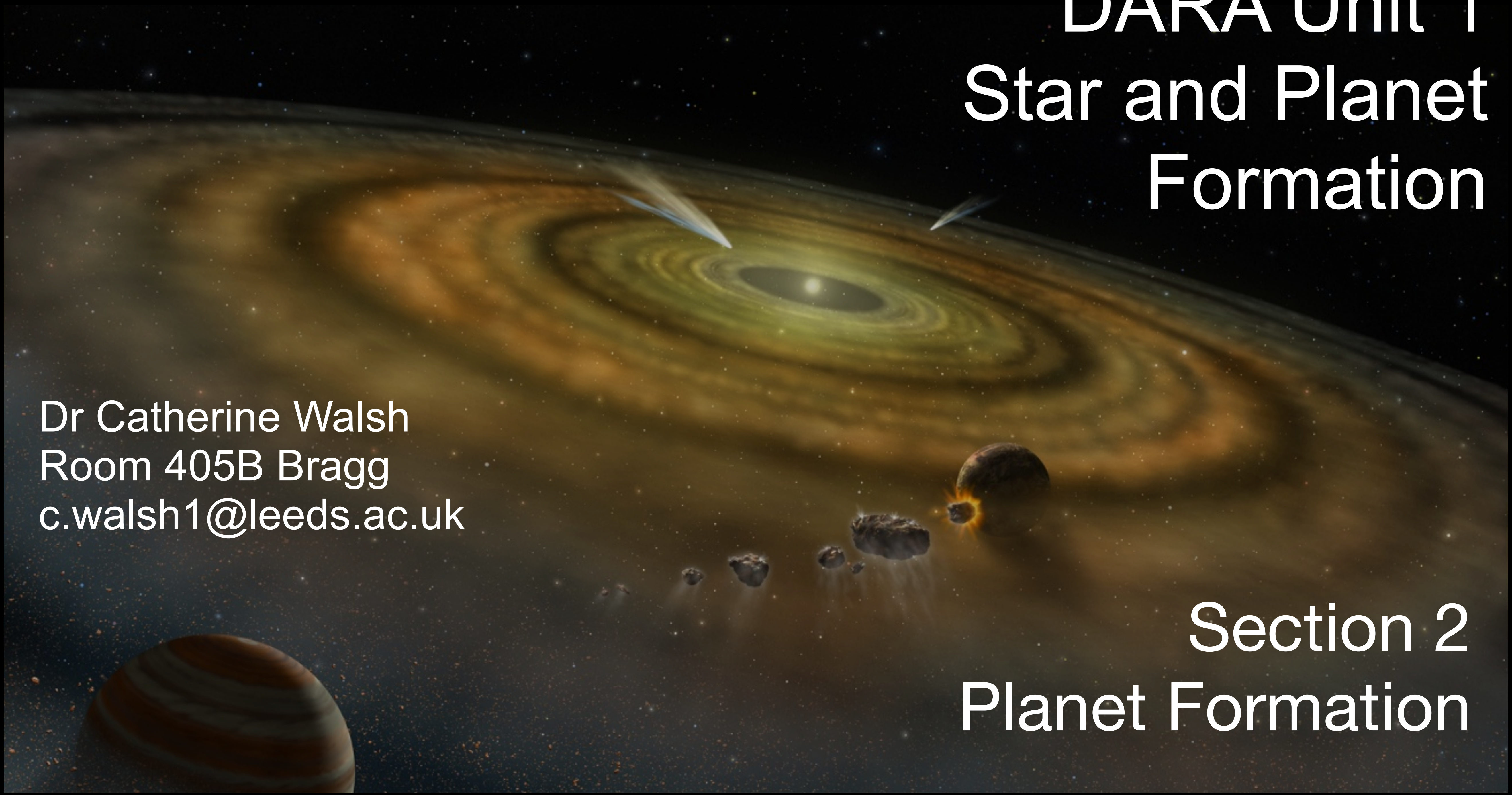
School of Physics and Astronomy
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

UNIVERSITY OF LEEDS

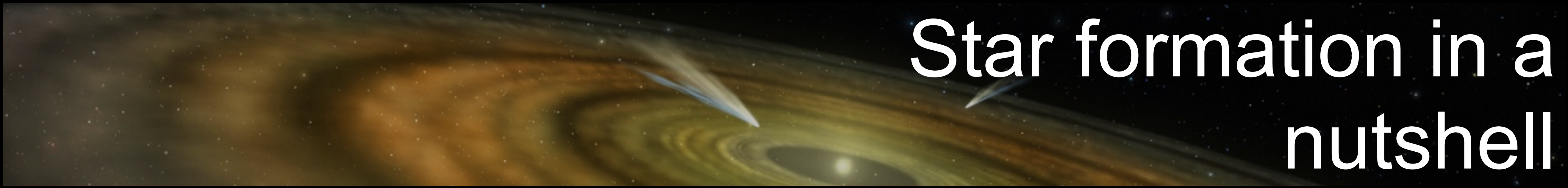


DARA Unit 1 Star and Planet Formation

Dr Catherine Walsh
Room 405B Bragg
c.walsh1@leeds.ac.uk

Section 2
Planet Formation

Star formation in a nutshell



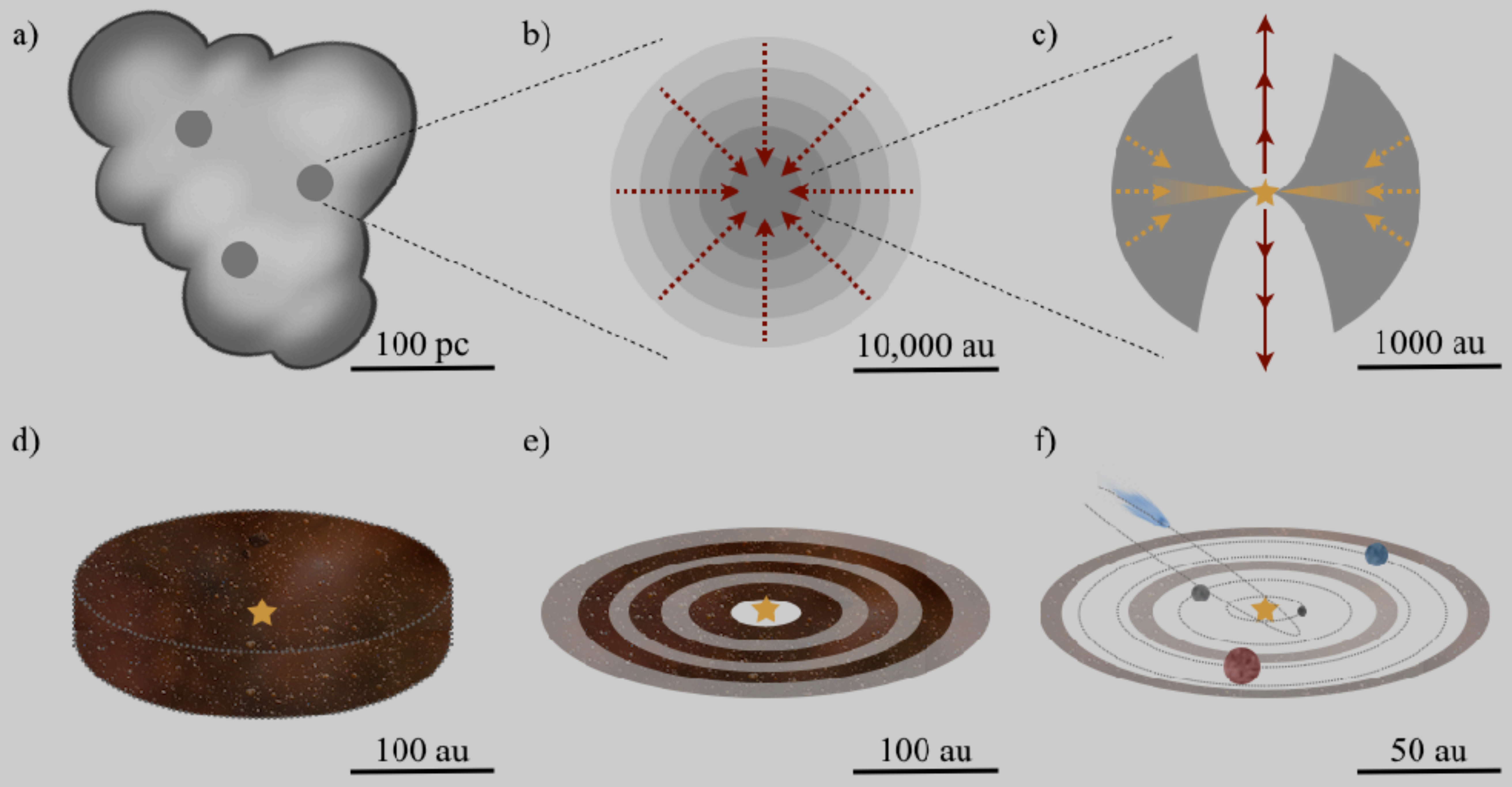
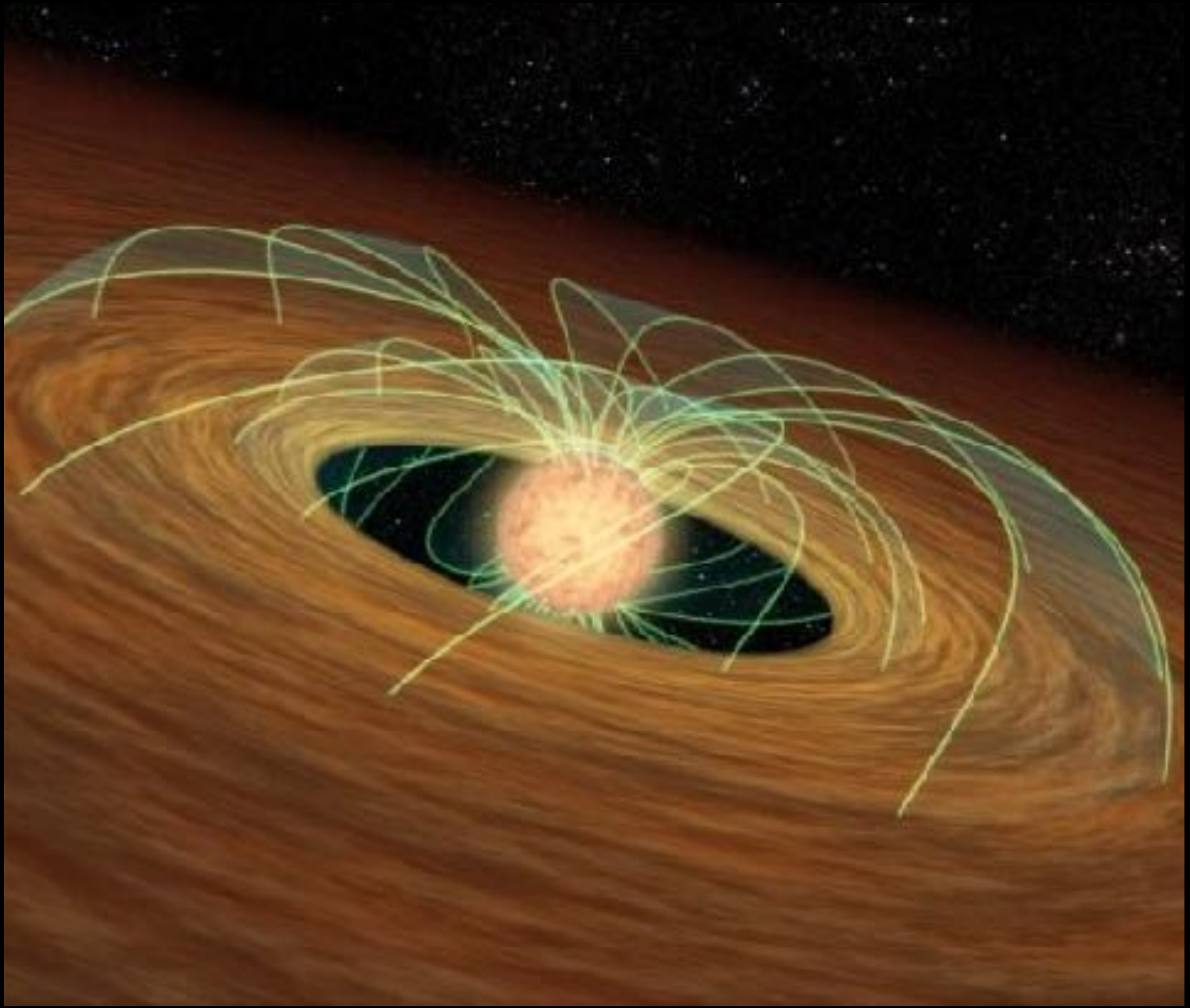
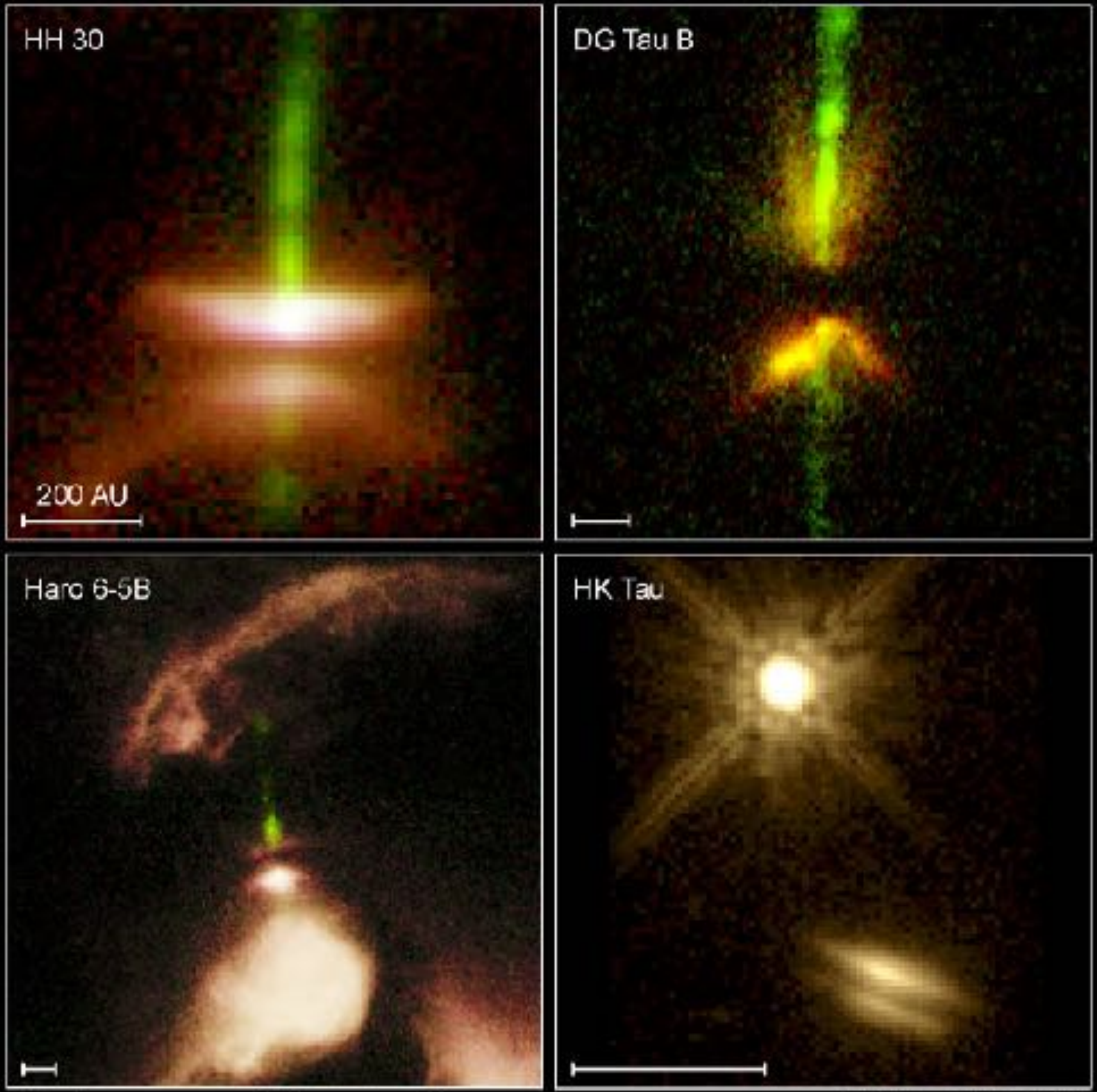


Image: C. Walsh (University of Leeds)

A star is born: pre-main-sequence stars

A new star accreting gas and dust from a surrounding *protoplanetary disc*



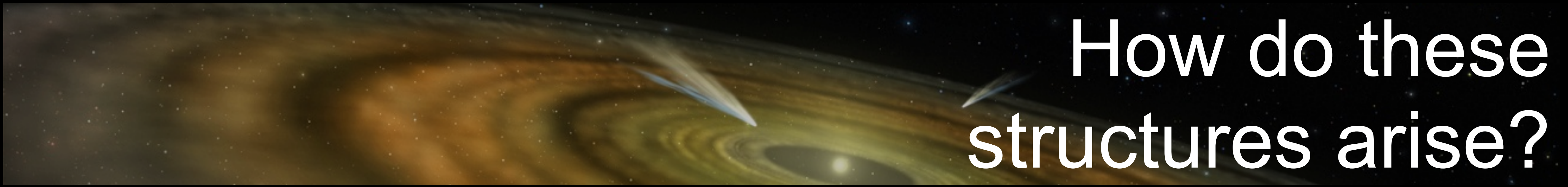


Disks around Young Stars **HST • WFPC2**

PRC99-05b • STScI OPO

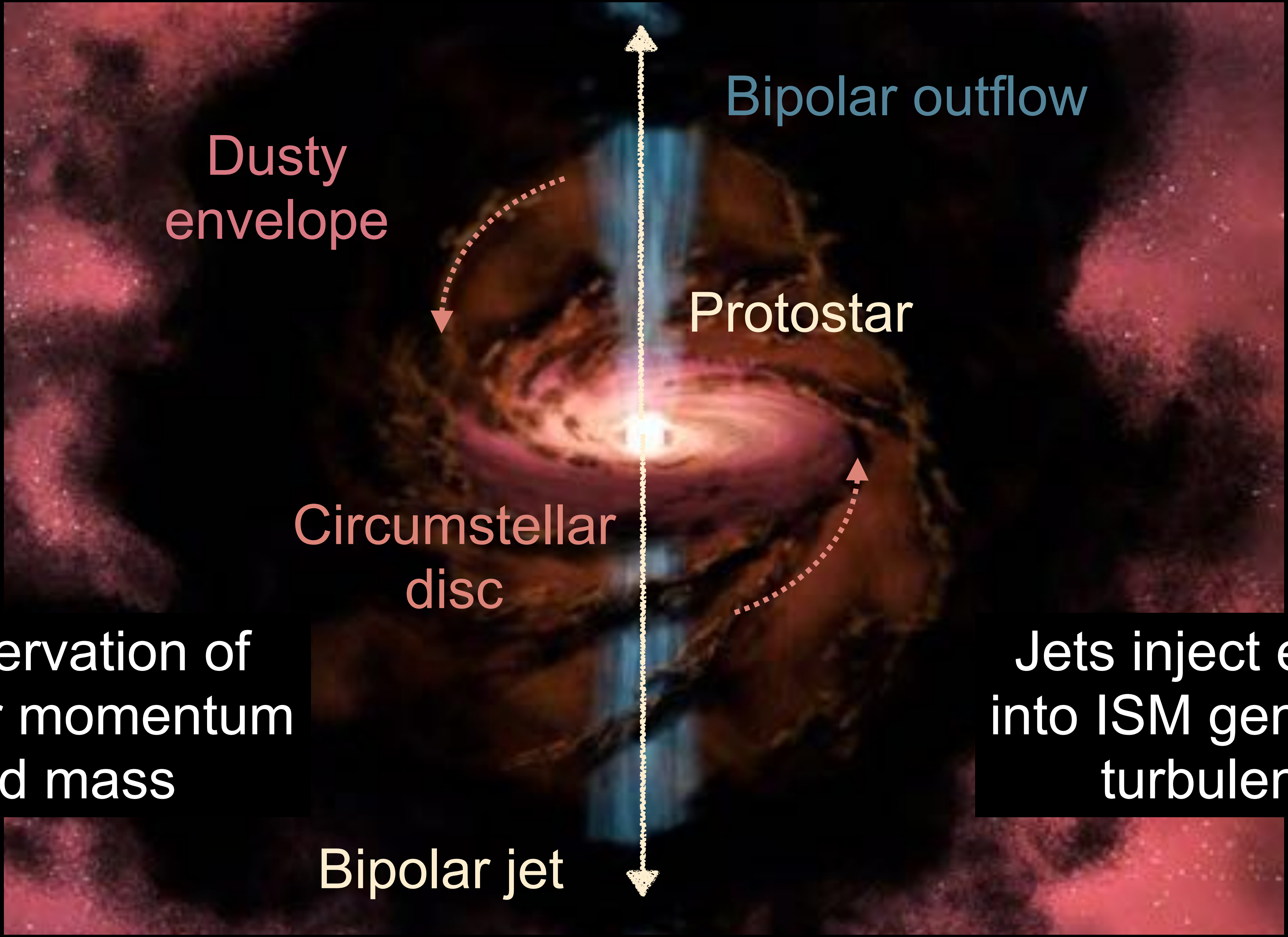
C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Images: K. Stappelfeldt (JPL) and colleagues, J. Krist (STScI), the WFPC2 Science Team, C. Burrows (STScI), and NASA/ESA/JPL-Caltech



How do these structures arise?

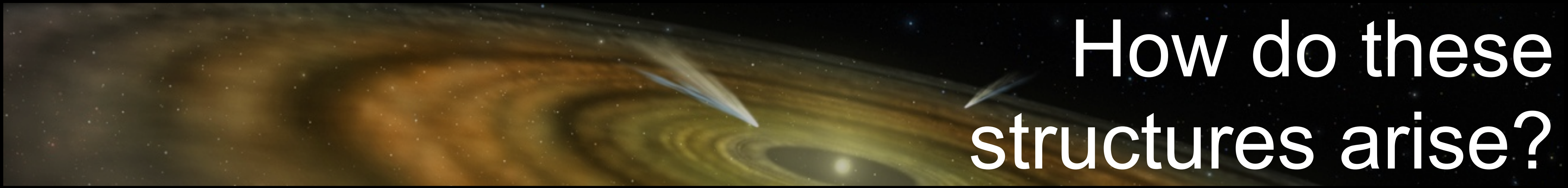
The modern view of star formation



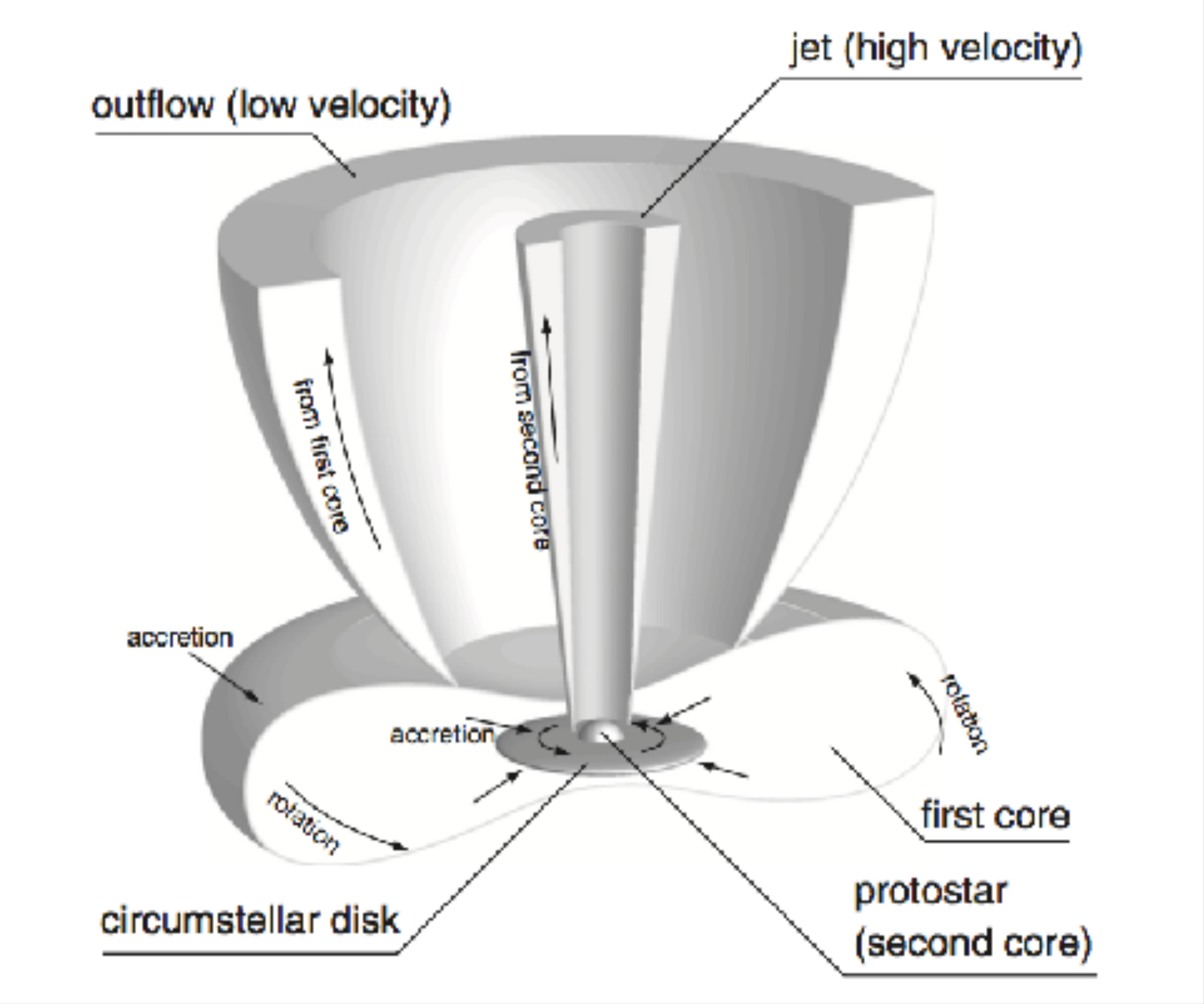
Conservation of angular momentum and mass

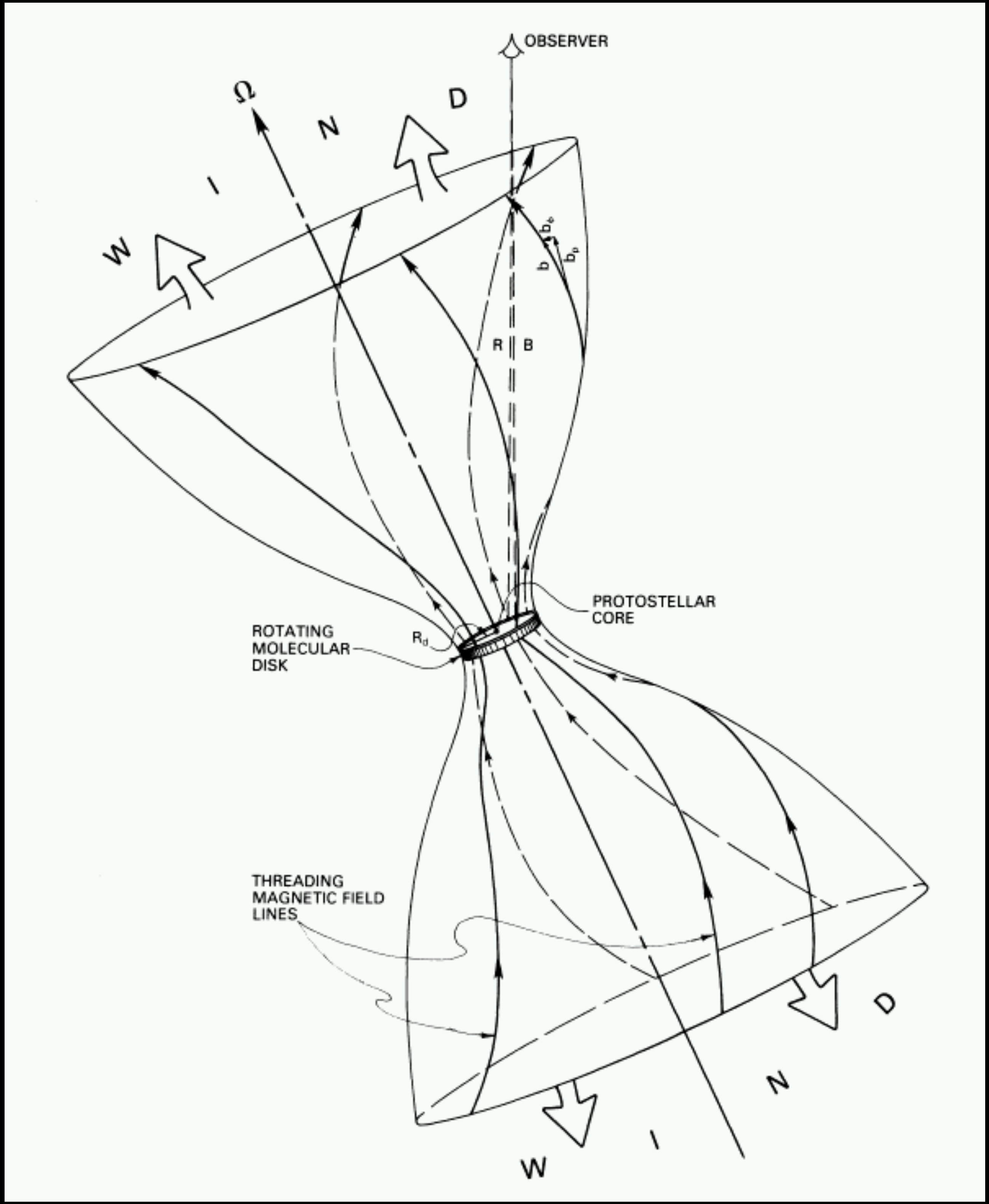
Jets inject energy into ISM generating turbulence

Image: NASA/ Caltech



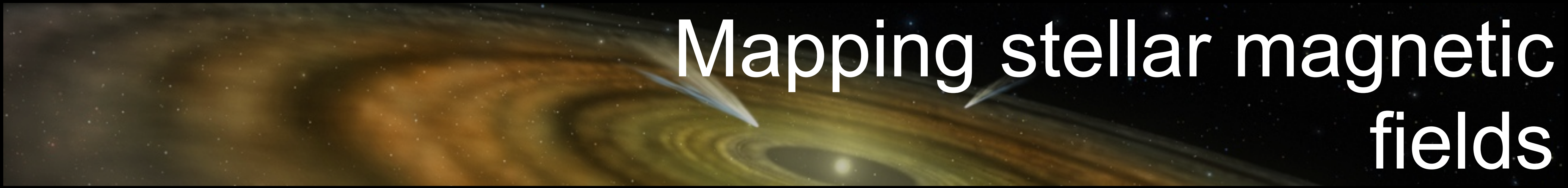
How do these structures arise?



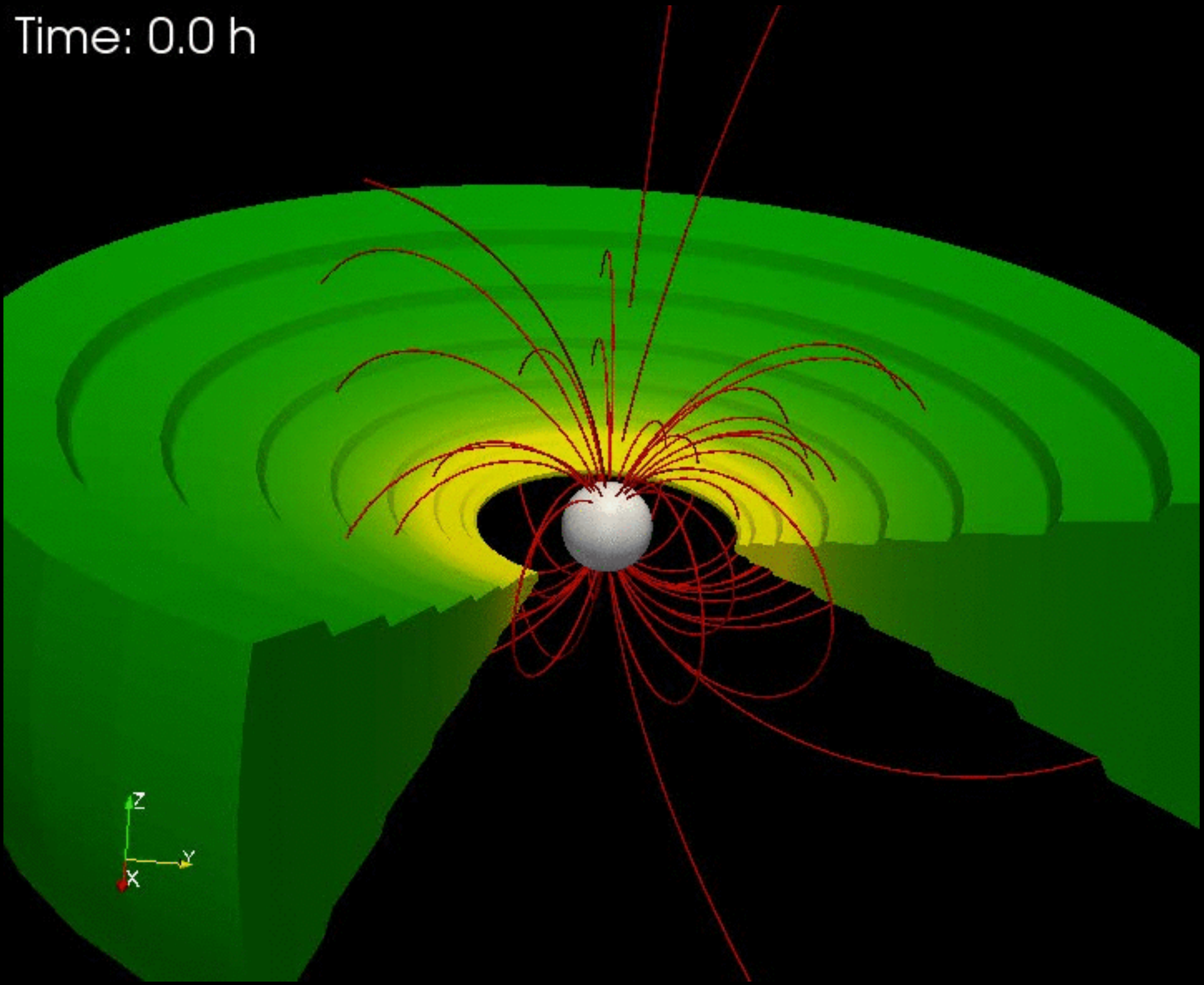


Magnetic fields

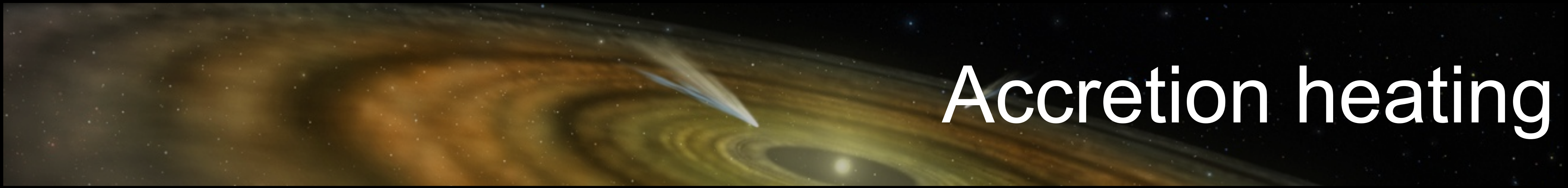
Images: Machida, M. N., et al. 2007, ApJ, 670, 1198; Inutsuka, S. 2012, PTEP, 1, 356



Mapping stellar magnetic fields



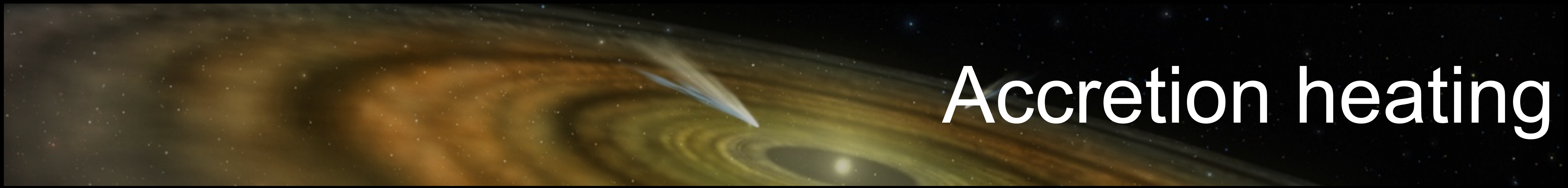
Movie: http://cerere.astropa.unipa.it/progetti_ricerca/HPC/gallery.htm; Orlando, S., et al. 2011, MNRAS, 415, 3380



Accretion heating

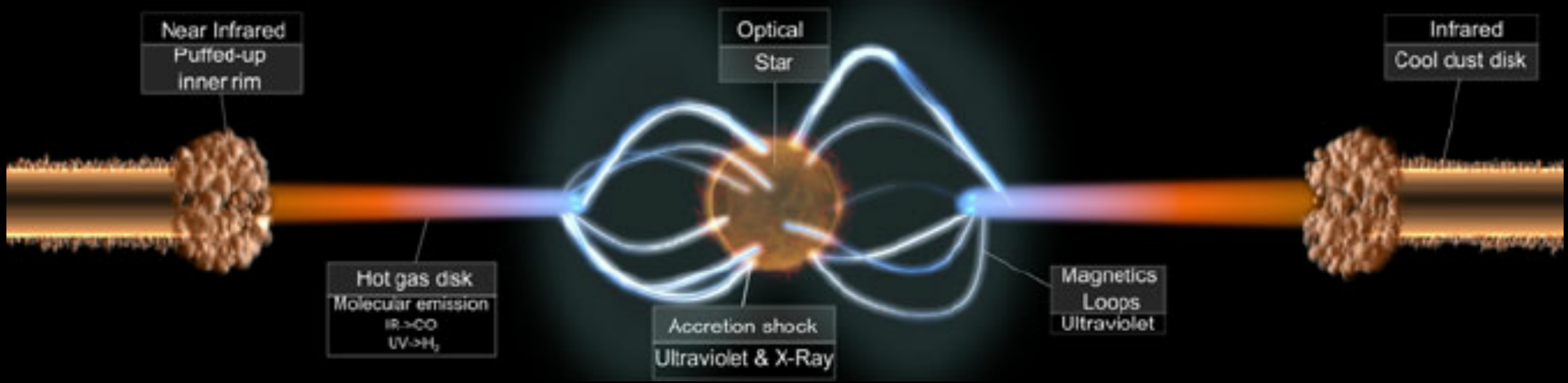
The tyres heat up: they are warmed up by friction between the tyres and the ground

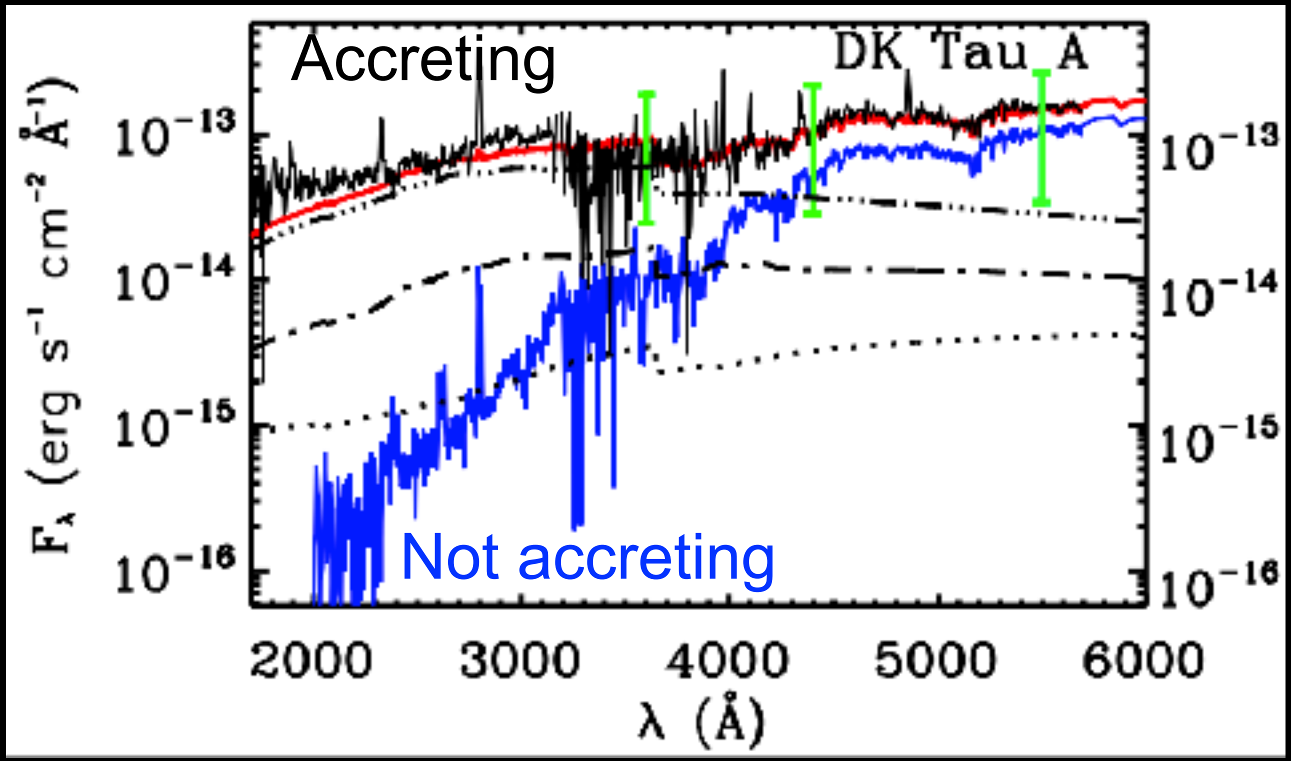
Movie: https://www.youtube.com/watch?v=jvuBe6b2iVk; FLIR/Red Bull Racing



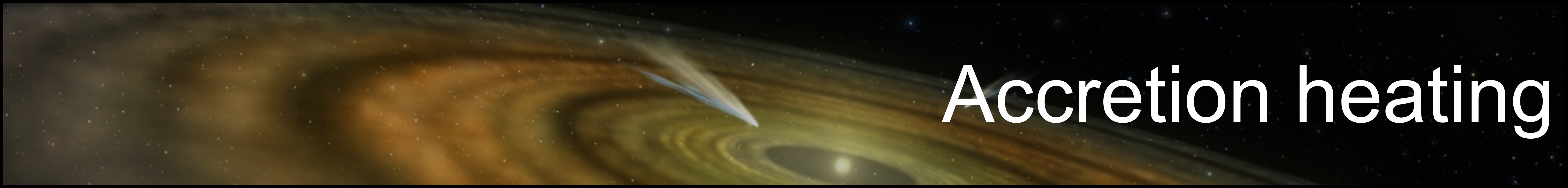
Accretion heating

Terminal velocity onto star is very high ~ 100 km/s: material accreting is shocked, very hot, and bright





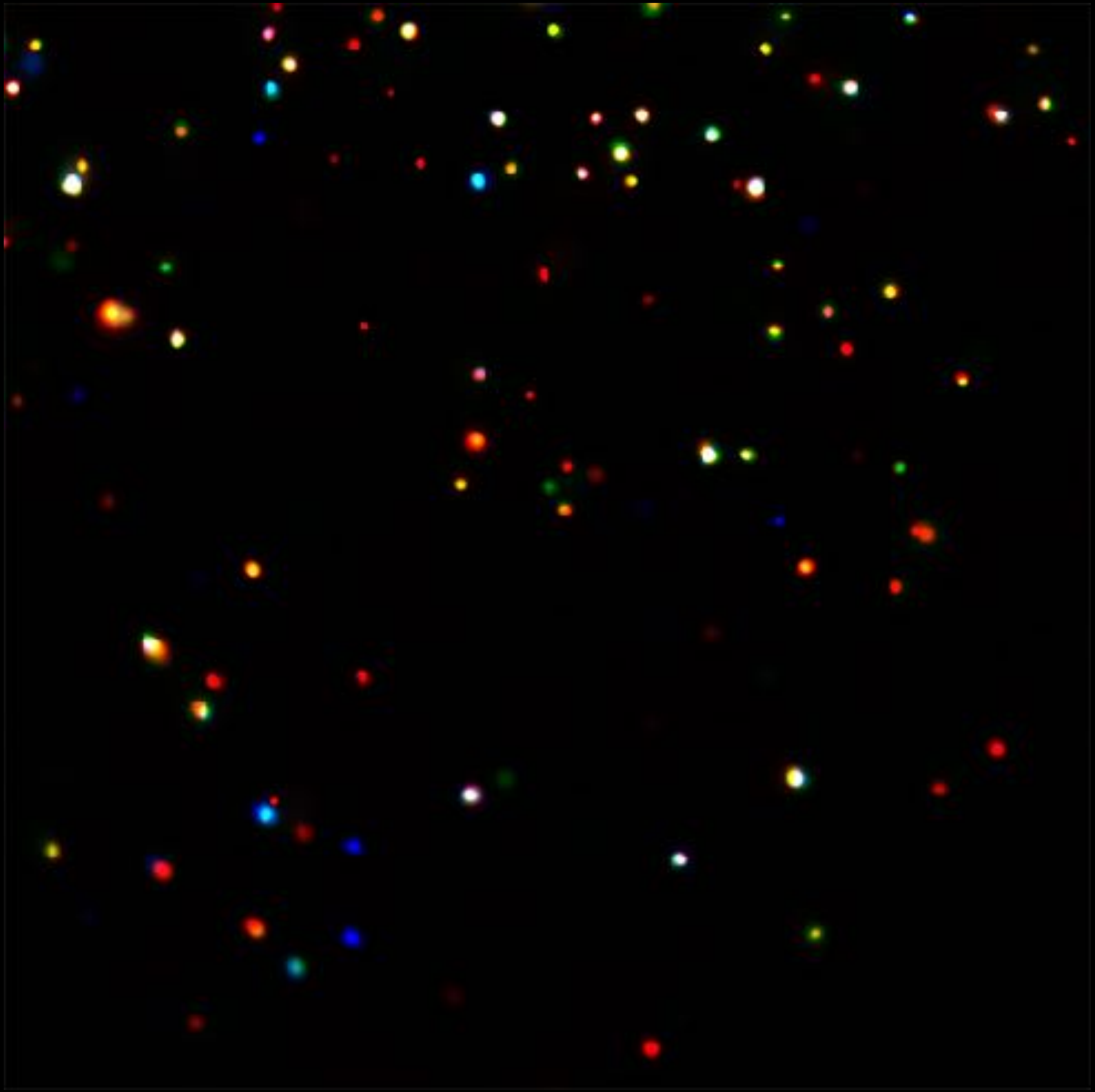
Images: de Castro, A. I. G. 2011, Exp. Astron., 30, 205; Ingleby, L., et al. 2013, ApJ, 767, 112



Accretion heating

M16 Composite
Optical (*Hubble*) & X-ray (*Chandra*)

M16
X-ray (*Chandra*)



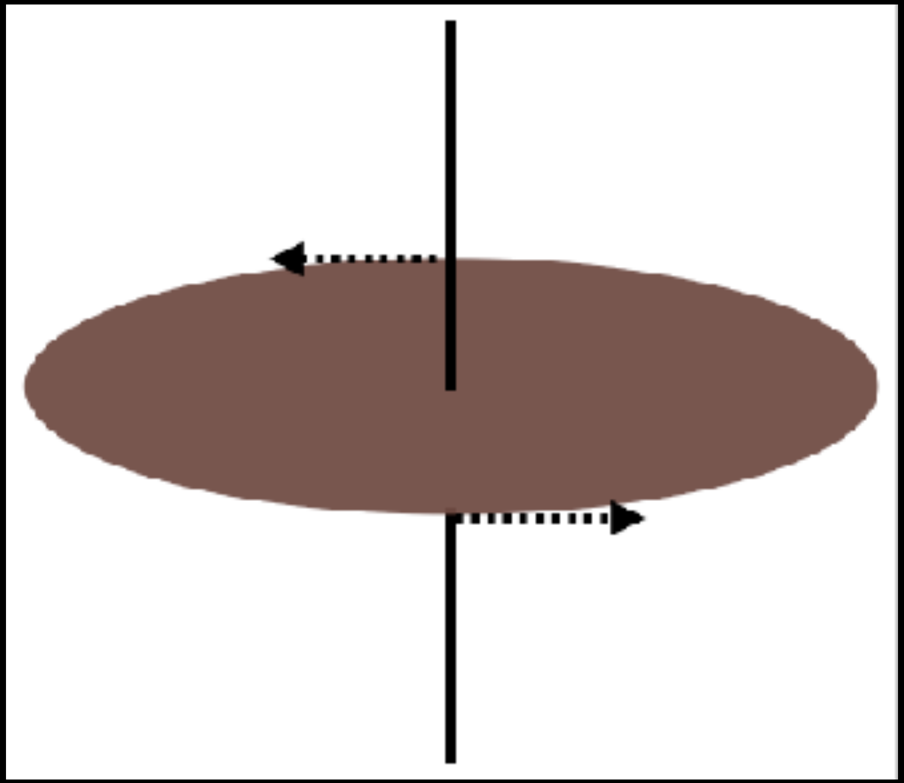
Images: X-ray: NASA/CXC/INAF/M.Guarcello et al.; Optical: NASA/STScI

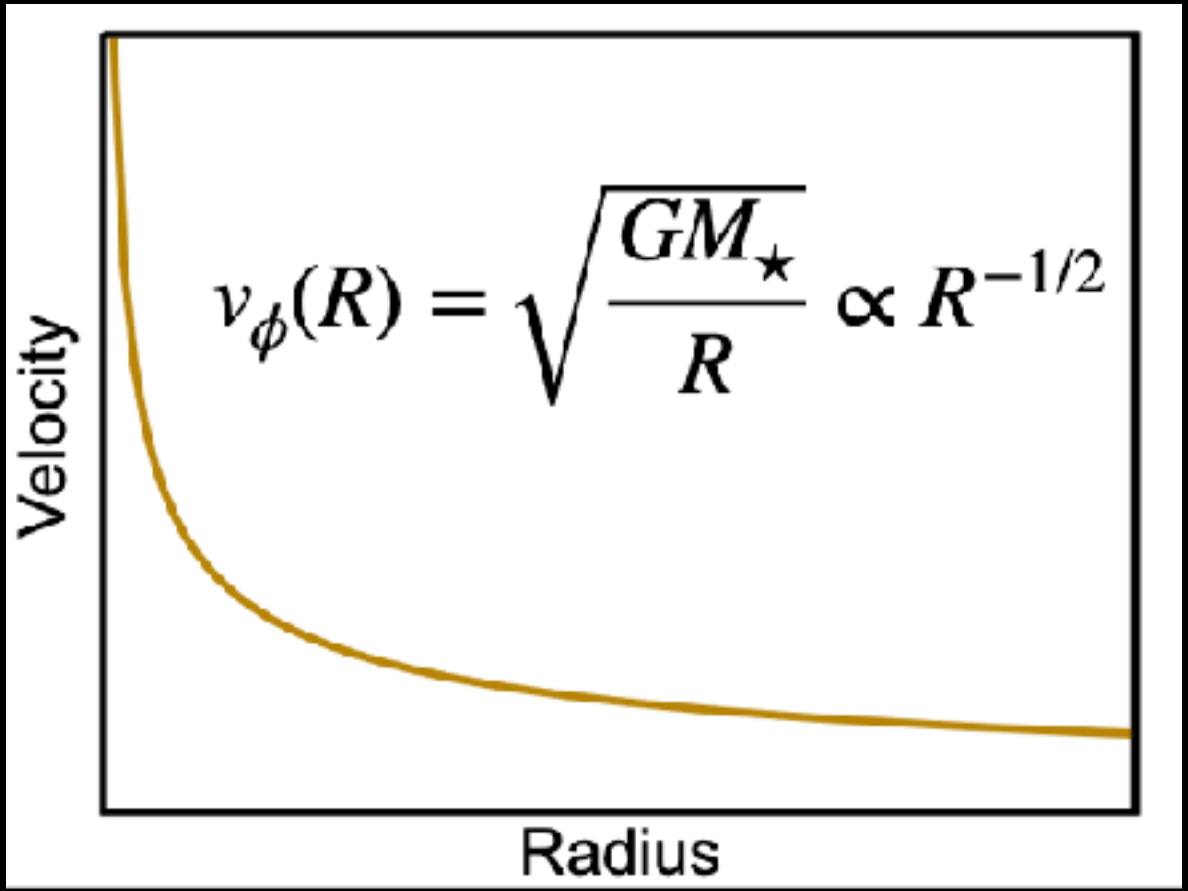
Accretion discs

Material falling onto a protostar will have substantial angular momentum: as a consequence, an accretion disk forms

Accretion disks are geometrically thin: $H << R$

The orbital velocity is (close to) Keplerian





$$v_\phi(R) = \sqrt{\frac{GM_\star}{R}} \propto R^{-1/2}$$

Accretion discs

Example: orbital velocity of the planets in the Solar System

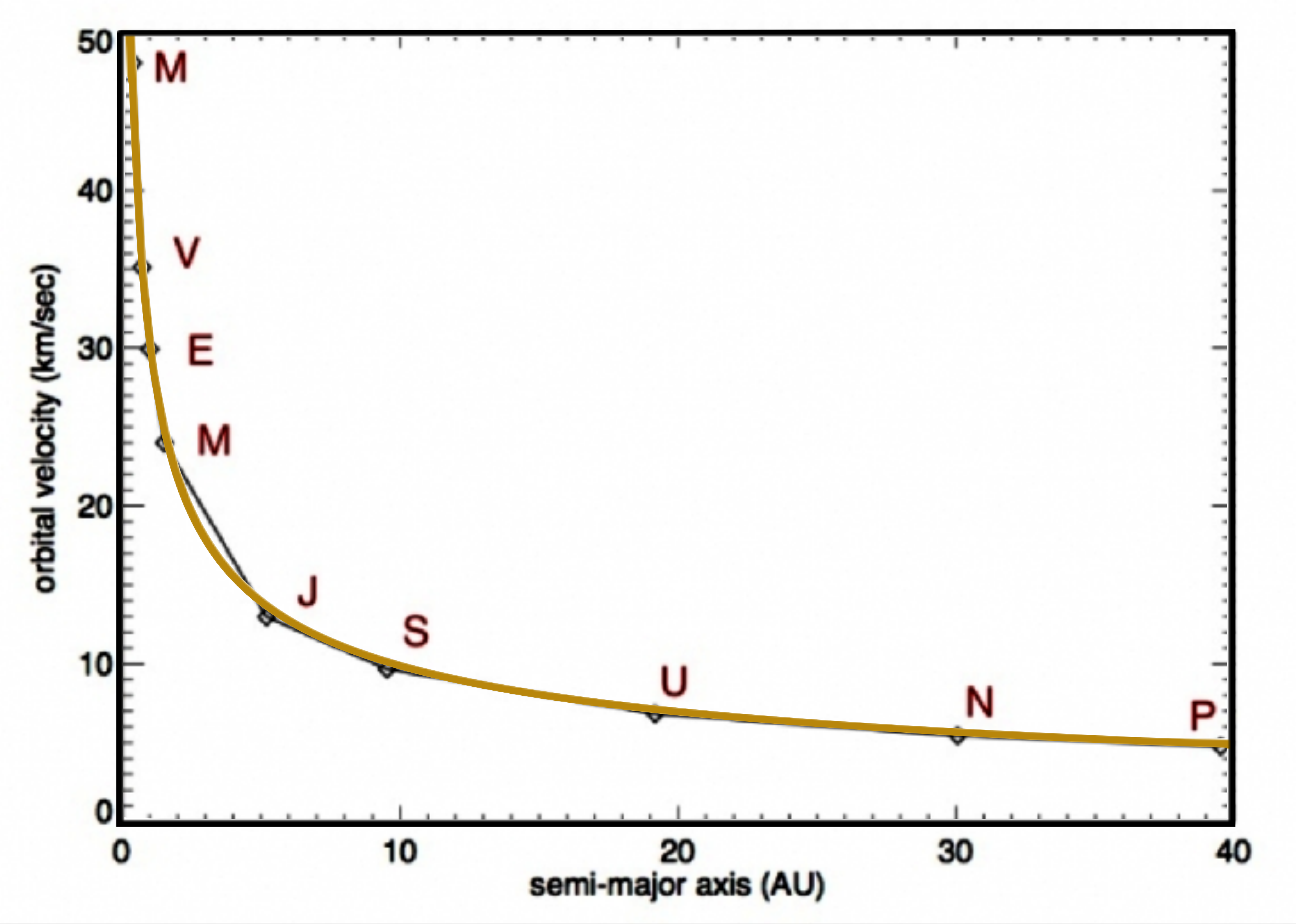
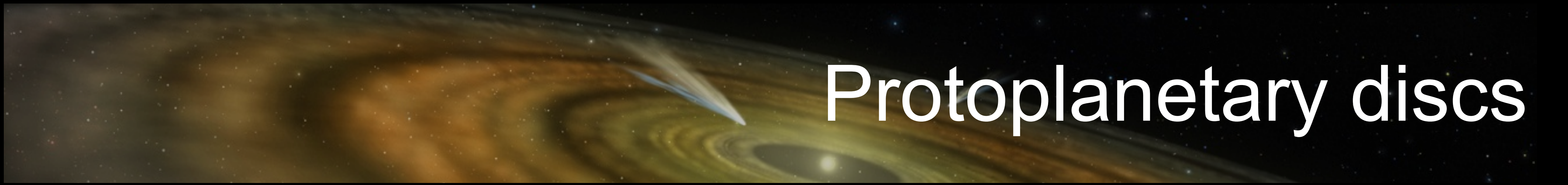
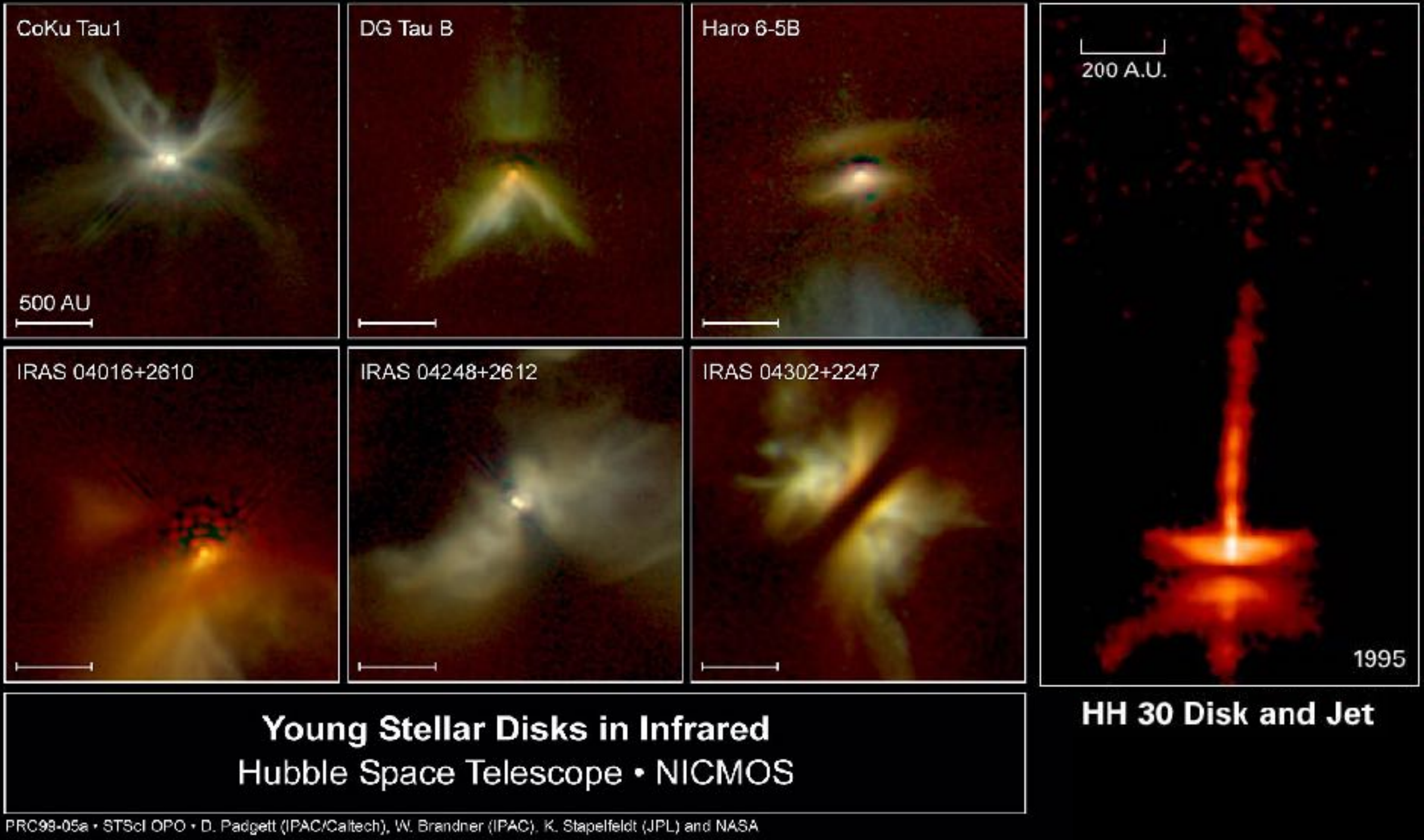


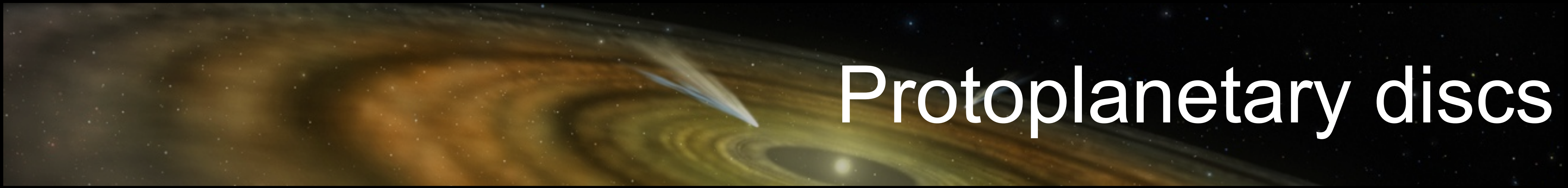
Image: https://www.e-education.psu.edu

Protoplanetary discs



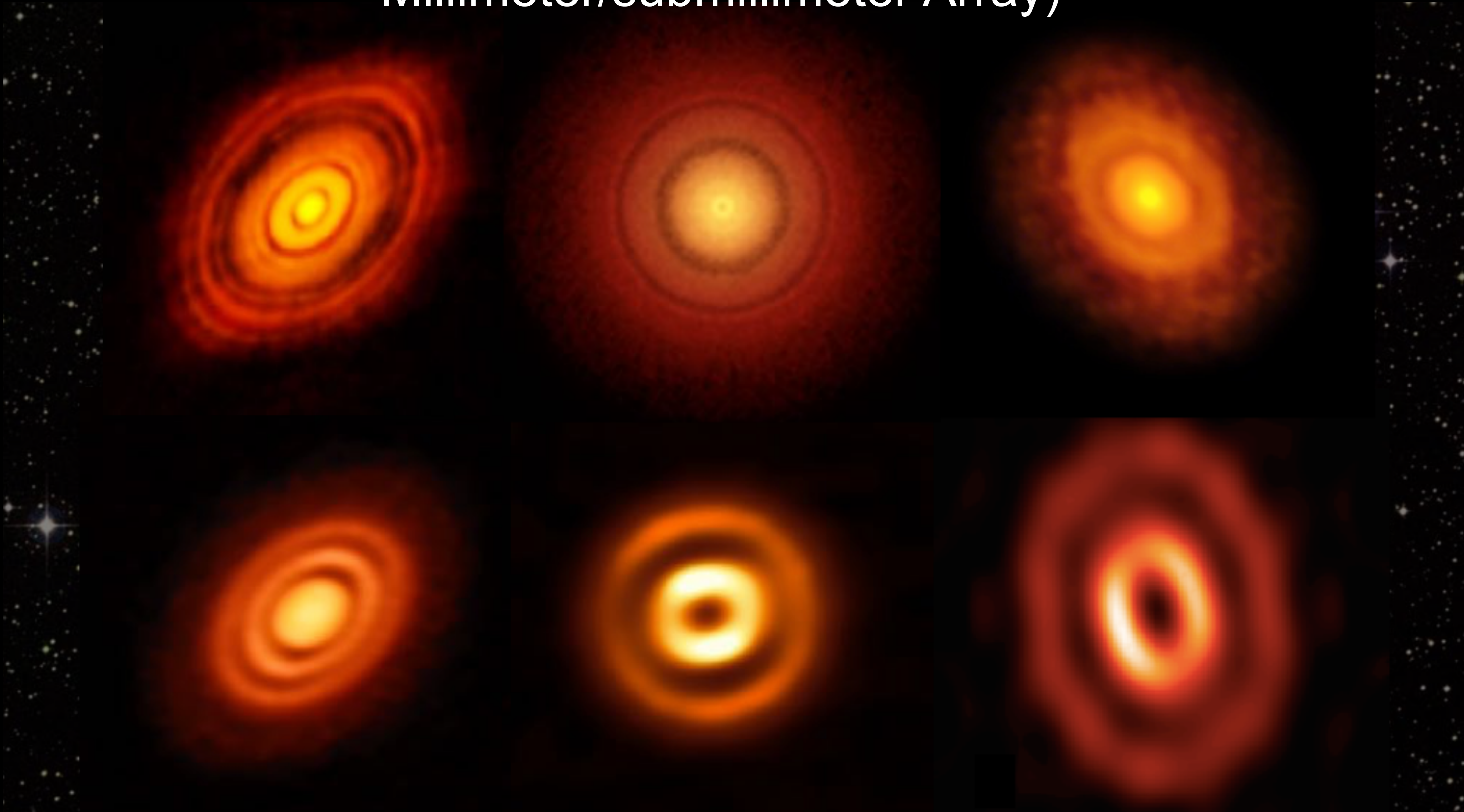


Images: NASA/A. Watson (UNAM)/STSCI

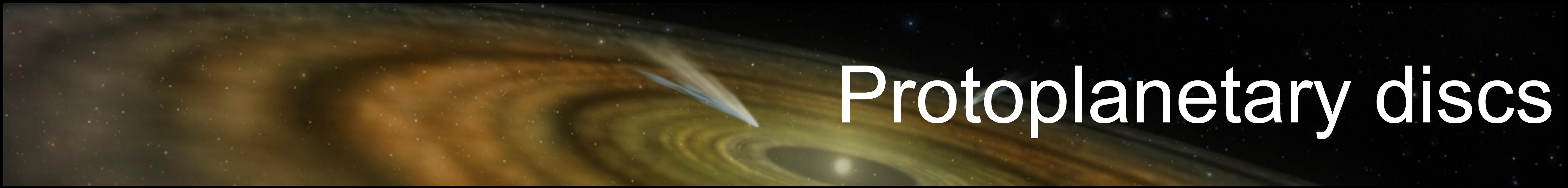


Protoplanetary discs

Protoplanetary disks at high resolution with ALMA (Atacama Large Millimeter/submillimeter Array)



ALMA Partnership, et al. 2015; Andrews et al. 2016; Cieza et al. 2016; Isella et al. 2016; Walsh et al. 2016; Fedele et al. 2017; van der Plas et al. 2017
Credits: S. Andrews, L. Cieza, A. Isella, A., Fedele, D., van der Plas, G., and ALMA (ESO/NAOJ/NRAO).



Protoplanetary discs

Modern optical/near-IR telescopes now employ coronagraphs to see scattered starlight from the disk: images from VLT/SPHERE

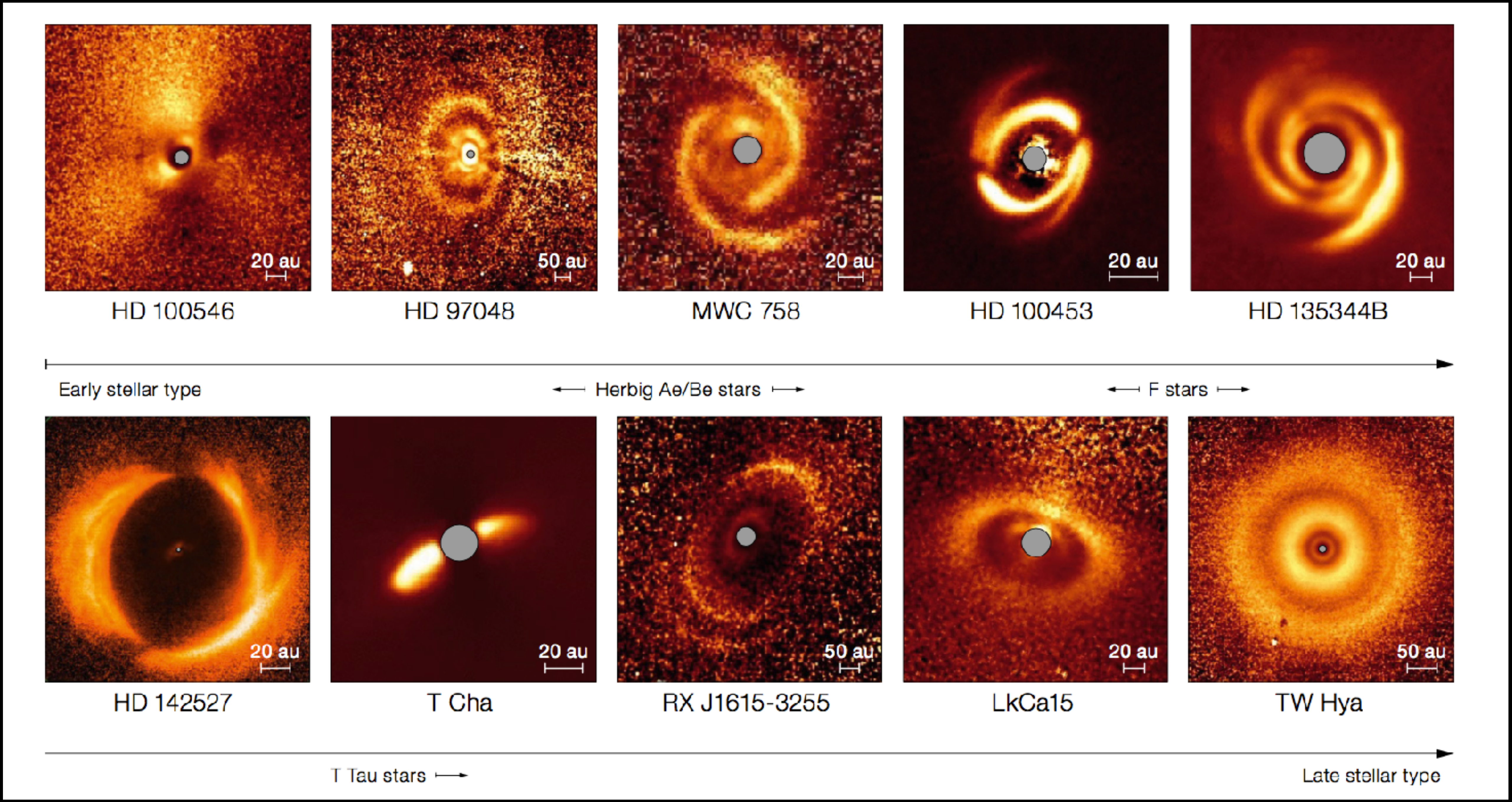
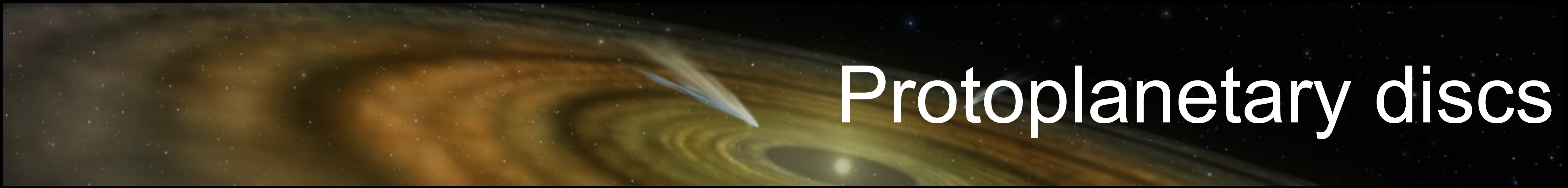


Image: Garufi et al. 2017, The Messenger, 169, 32



Protoplanetary discs

Exploitation of the knowledge of keplerian rotation can reveal orbiting molecular disks via double-peaked line profile

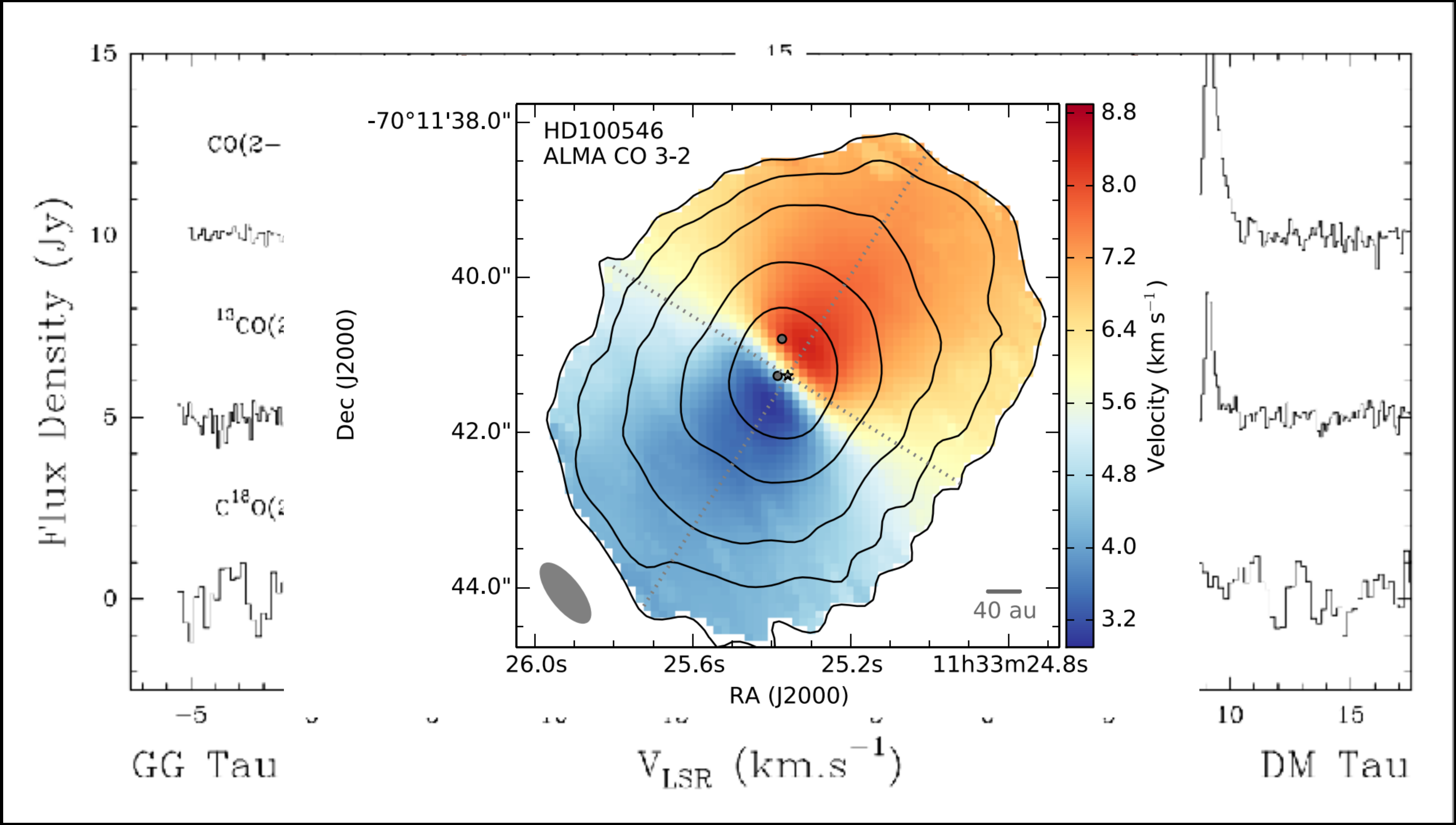
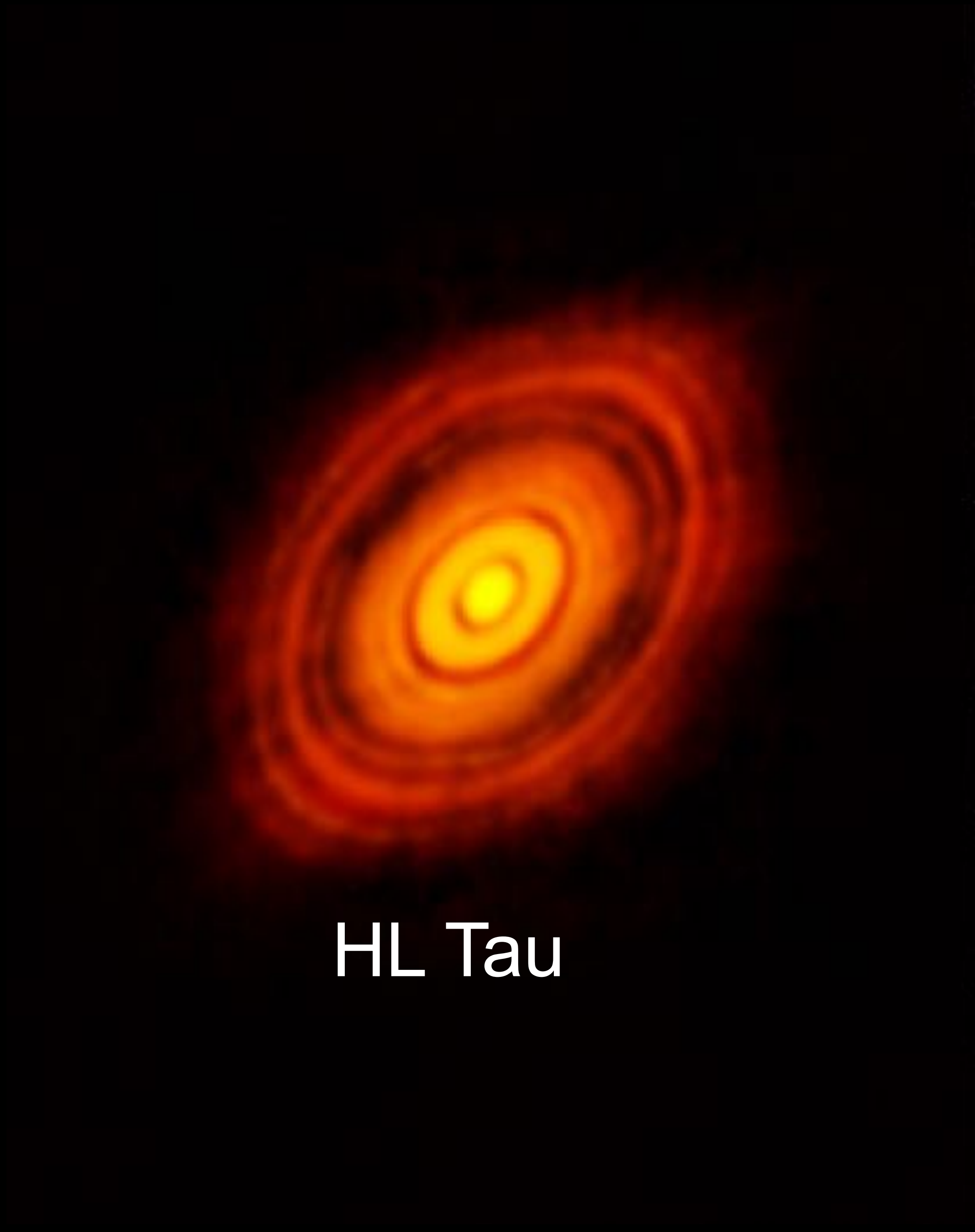


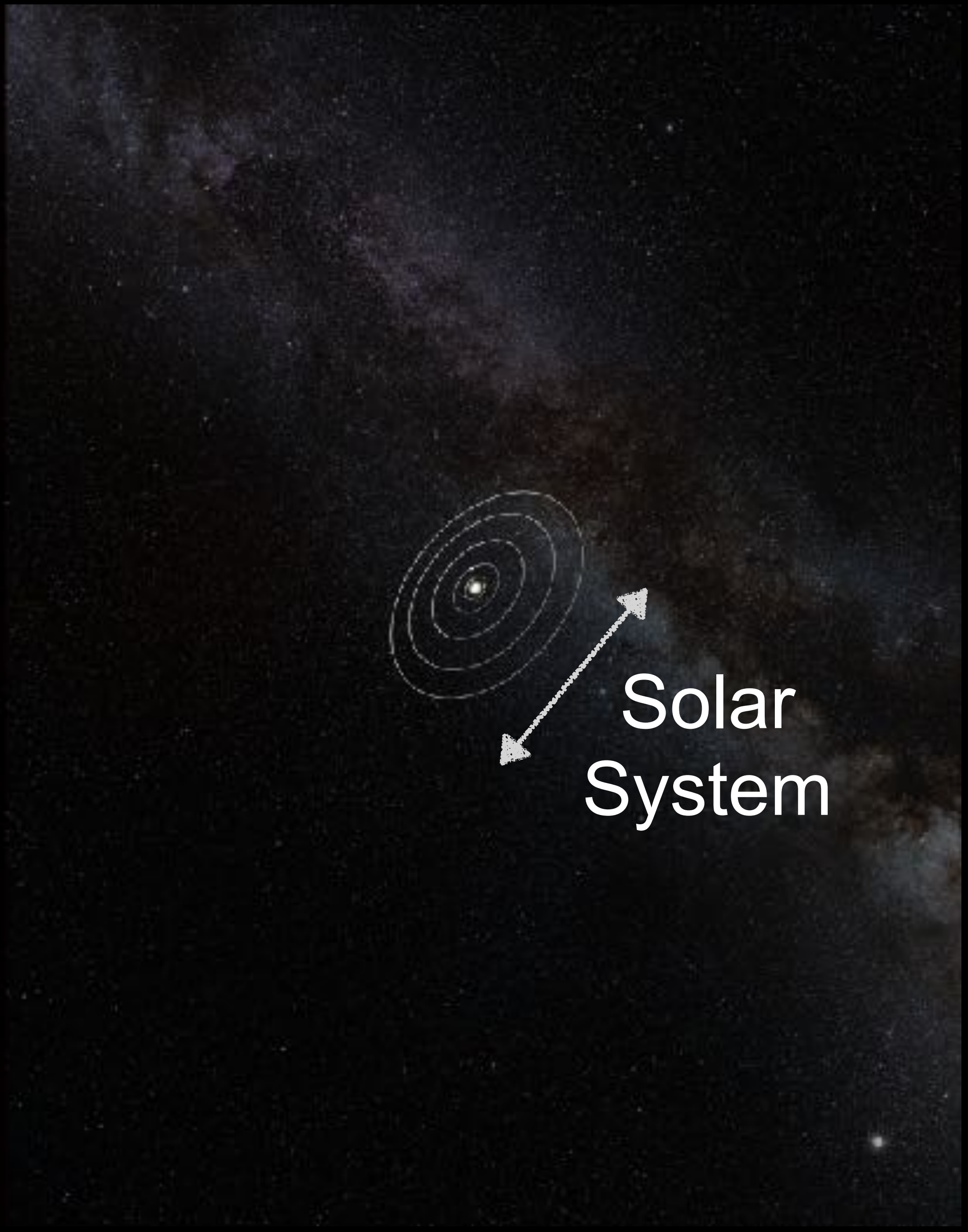
Image: Dutrey, et al. 1997, A&A, 317, L55

How do planets form?

From dust and gas in protoplanetary discs



HL Tau

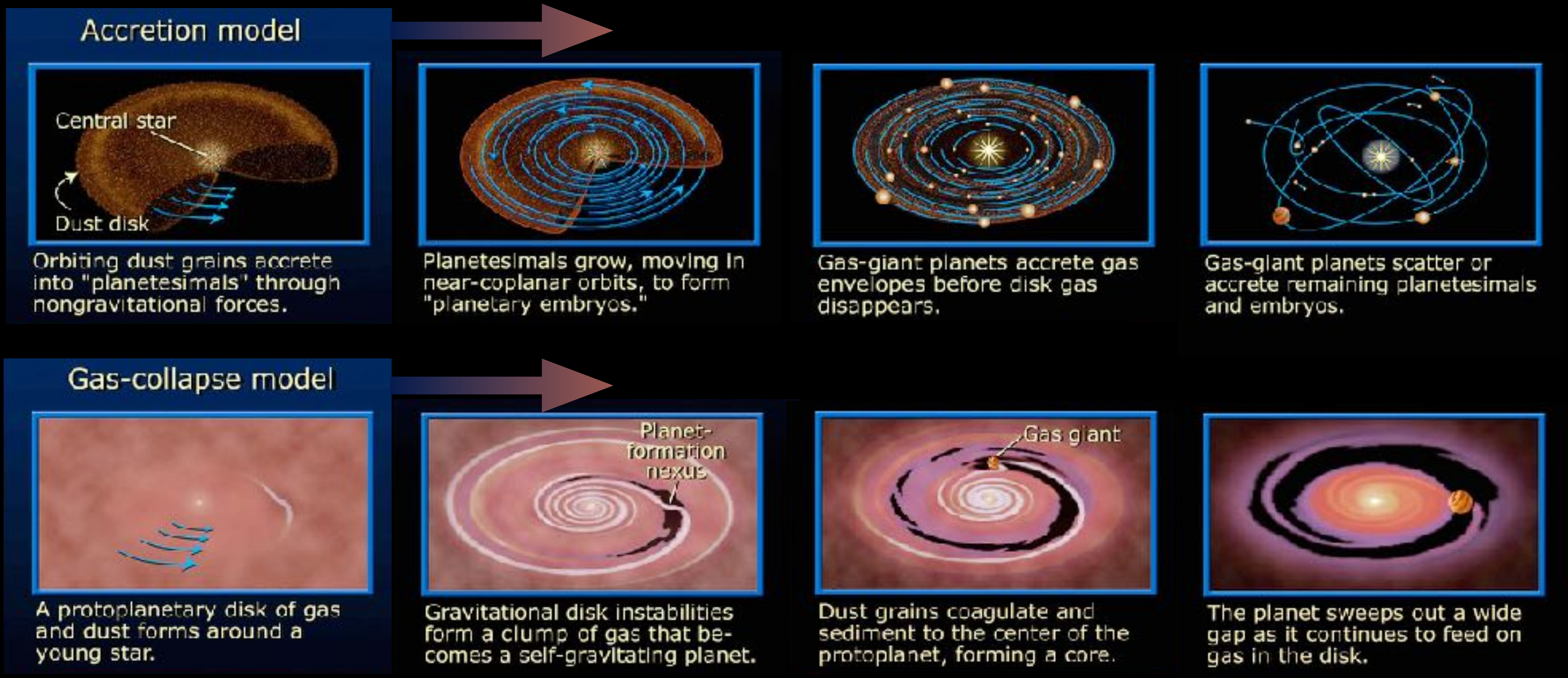


Solar System

Image: ALMA (ESO/NAOJ/NRAO)/NASA/ESA

How do planets form?

There remain many questions on the physics of planet formation



Accretion model

Orbiting dust grains accrete into "planetesimals' through nongravitational forces.

Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

Gas-giant planets accrete gas envelopes before disk gas disappears.

Gas-giant planets scatter or accrete remaining planetesimals and embryos.

Gas-collapse model

A protoplanetary disk of gas and dust forms around a young star.

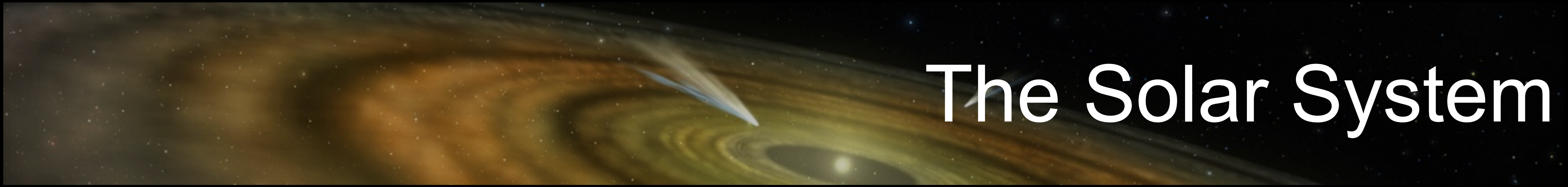
Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.

Dust grains coagulate and sediment to the center of the protoplanet, forming a core.

The planet sweeps out a wide gap as it continues to feed on gas in the disk.

Both mechanisms are possible, depending on the properties of the protoplanetary disk

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



The Solar System

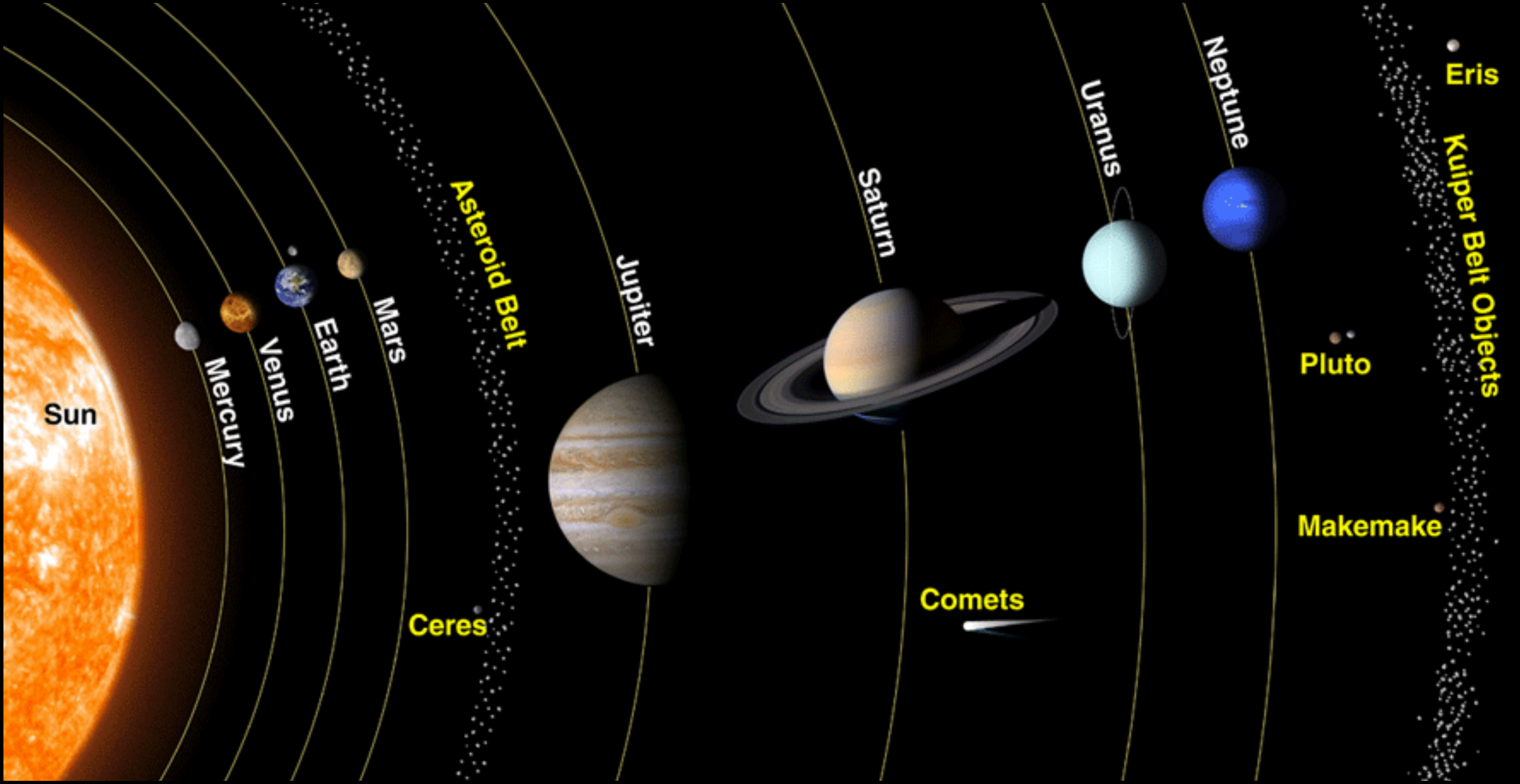
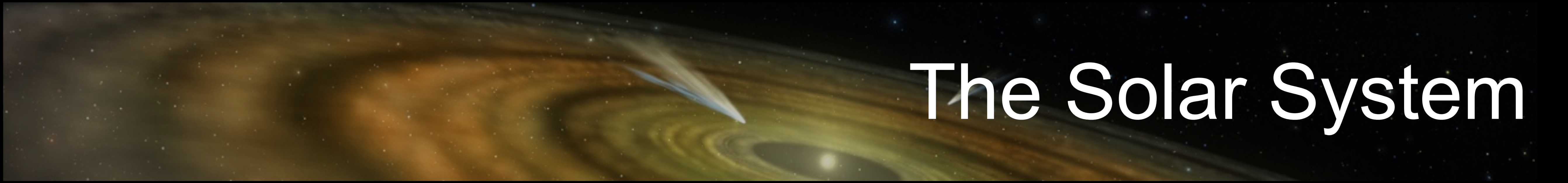


Image: https://spaceplace.nasa.gov/



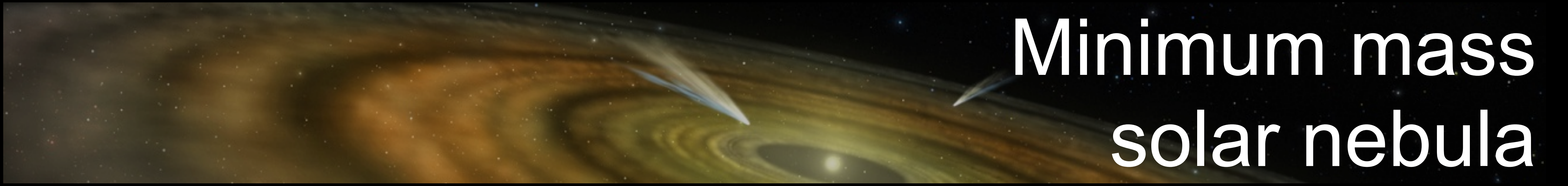
The Solar System

- A useful piece of information when considering the formation of our Solar System is the minimum amount of mass that is required to build all the bodies orbiting the Sun.

- This Minimum Mass Solar Nebula (MMSN) contains roughly a few dozen times the mass of Jupiter.

- This matter will be distributed in the original disk around the Sun. The disk contains dust and gas. However, the composition of the material in the disk changes as function of distance from the star.

- This is where the concept of the "snow line" comes in. At distances further away, ice coatings on dust grains increase the mass of solids available for building planetesimals.



Minimum mass solar nebula

By looking at the mass distribution in the Solar System, Hayashi (1981) concluded that the protoplanetary disk around the young Sun had to have had (at least) the following mass distribution

$$\Sigma_{\text{gas}} = 1700 \left(\frac{r}{\text{au}}\right)^{-3/2} \text{ g cm}^{-2}$$

$$\Sigma_{\text{solids}} = 7.1\, \text{F}_{\text{snow}} \left(\frac{r}{\text{au}}\right)^{-3/2} \text{ g cm}^{-2}$$

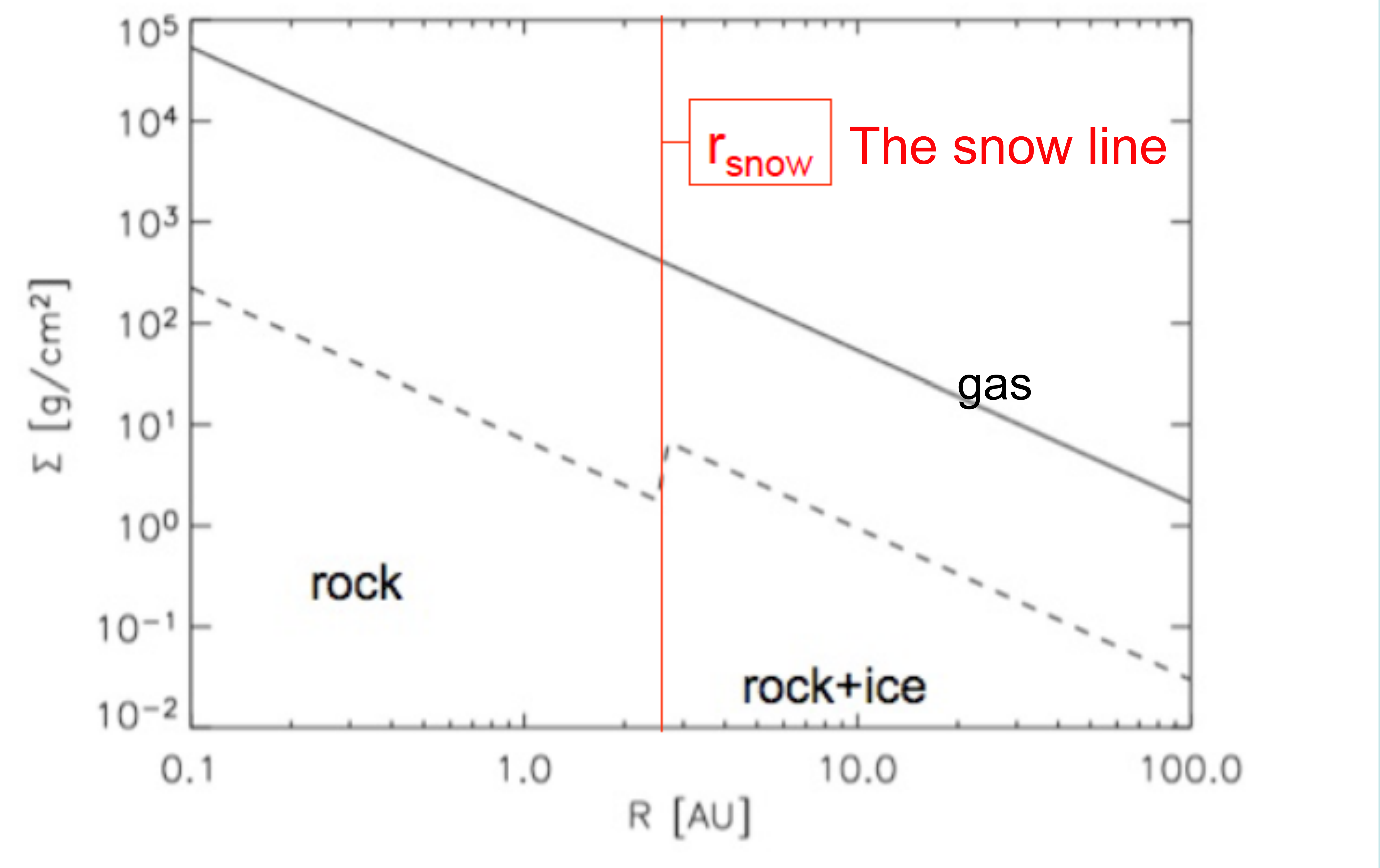
$$\text{F}_{\text{snow}} = \begin{cases} 1, & r < r_{\text{snow}} \\ 4.2, & r \geq r_{\text{snow}} \end{cases}$$

$$M_D = \int_0^R 2\pi\Sigma(r)\, dr$$

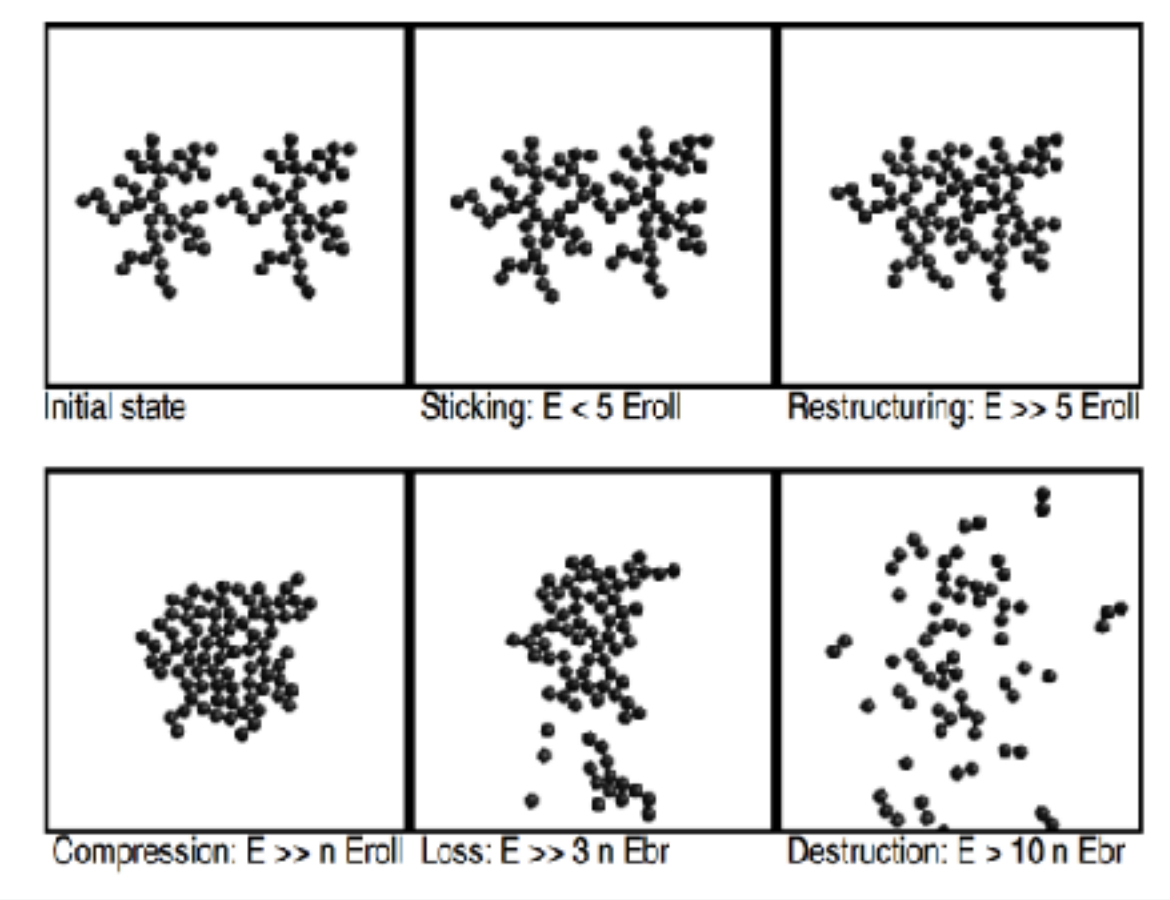
F_{snow} is the solid mass enhancement due to freeze out (sticking) of water onto the dust grains beyond the snow line

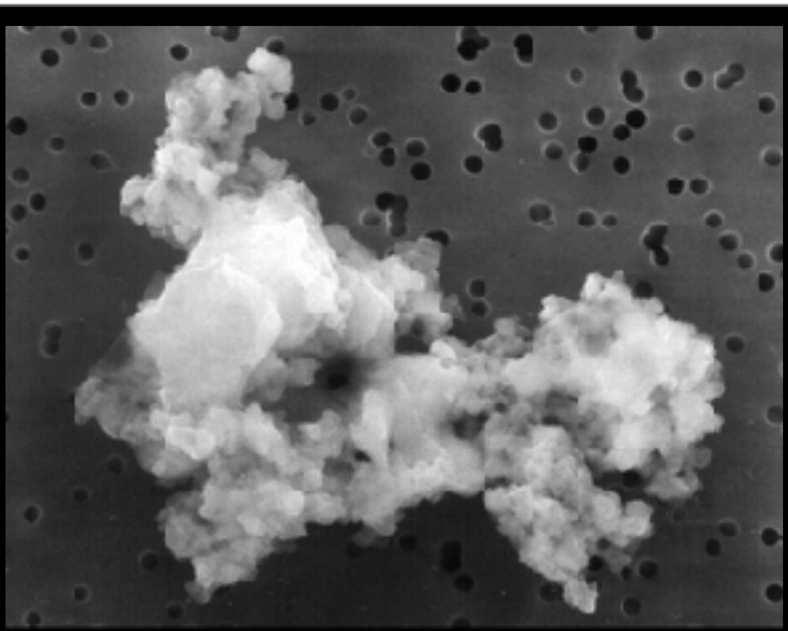
Hayashi 1981, PTPS, 70, 35

Minimum mass solar nebula



Condensation and growth of solid bodies



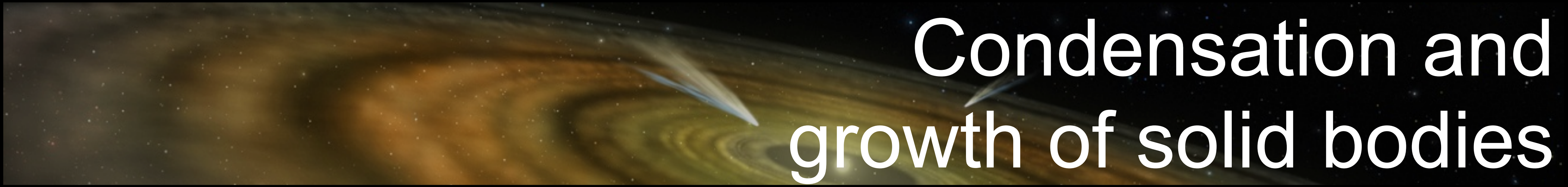


The mechanical and chemical processes related to grain agglomeration are poorly understood.

Loosely packed fractal structures that are held together by van der Waals forces may be formed.

Have some observational information from interplanetary dust particles (IDPs).

Image: NASA / Domnik et al. 2007, PPV, 783



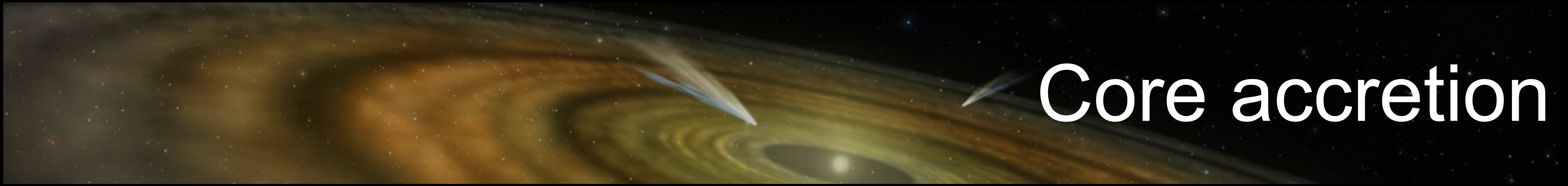
Condensation and growth of solid bodies

Hypothesis 1: if the nebula is quiescent the dust and small particles settle into a layer thin enough to be gravitationally unstable to clumping, and planetesimals are formed. The planetesimals produced have sizes of the order of ~ 1 km.

Hypothesis 2: if the nebula is turbulent growth continues via simple two-body collisions. The growth of solid bodies from mm to km size must occur very quickly but the related physics is poorly understood.

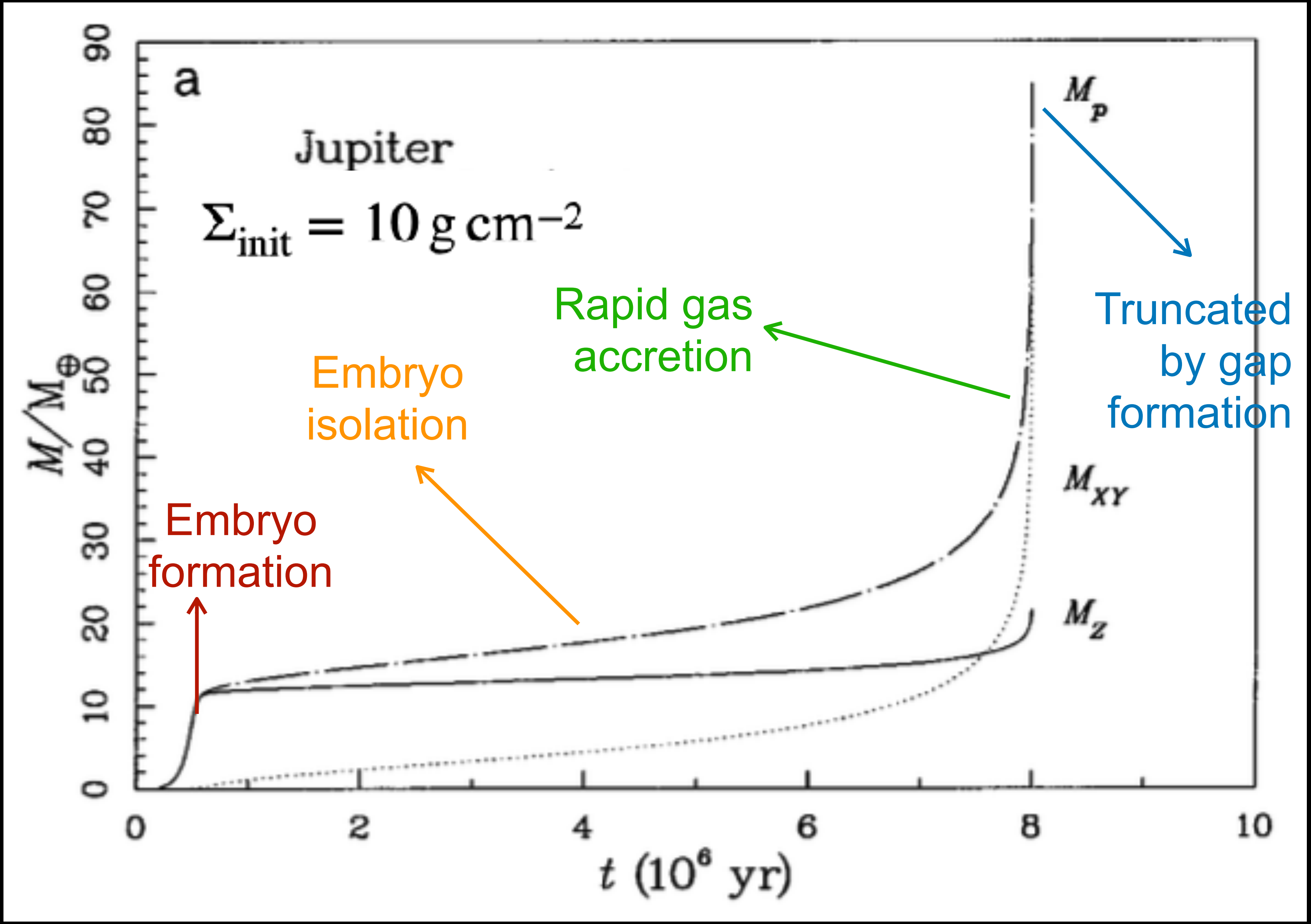
Molecular forces can lead to ~ km-sized planetesimals by coagulation (van der Waals binding energies: ~ 10^3 erg g^{-1} ~ gravitational binding energy of a 1 km body.)

Then, when size > 1 km, gravity takes over and mutual gravitational perturbations become important.



Core accretion

The first fully consistent time-dependent models of giant planet growth were published by Pollack et al. (1996).



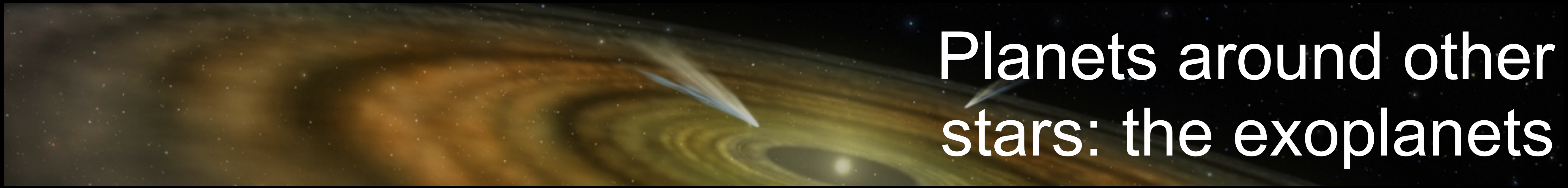
Embryo formation

Embryo isolation

Rapid gas accretion

Truncated by gap formation

Image: Pollack et al. 1996, Icarus, 124, 62



Planets around other stars: the exoplanets

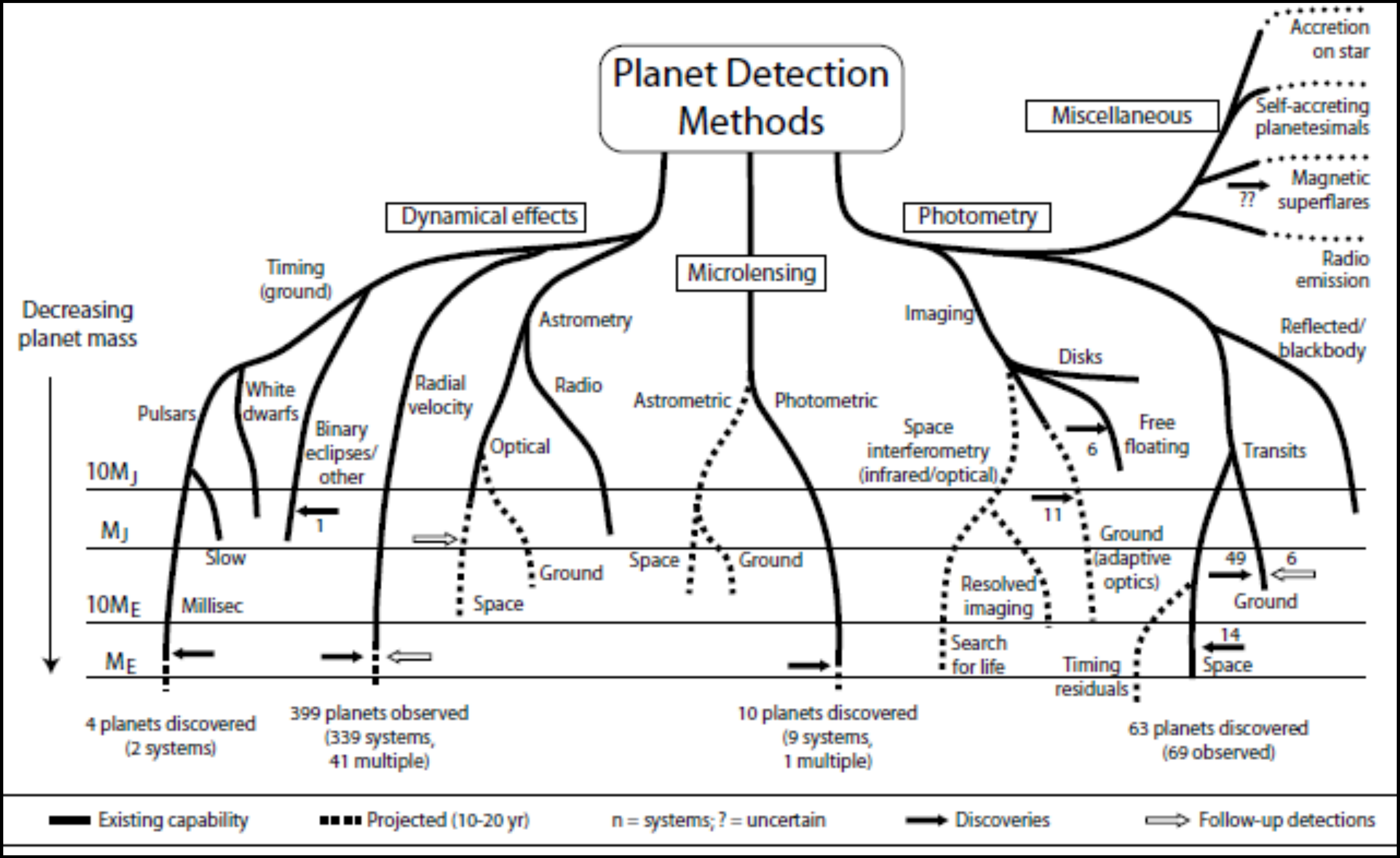
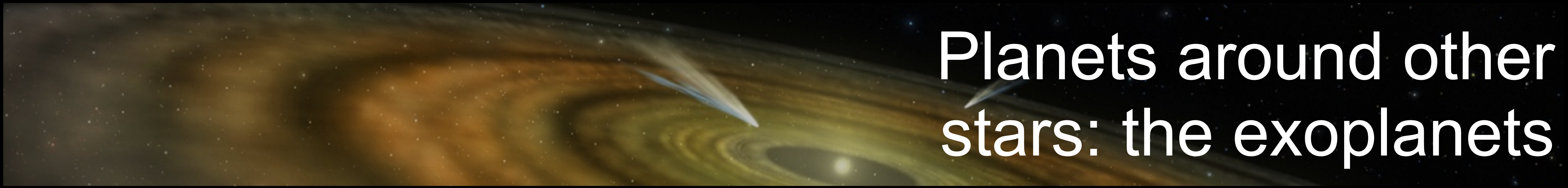


Image: Perryman 2000, RPP, 63, 1209



Planets around other stars: the exoplanets

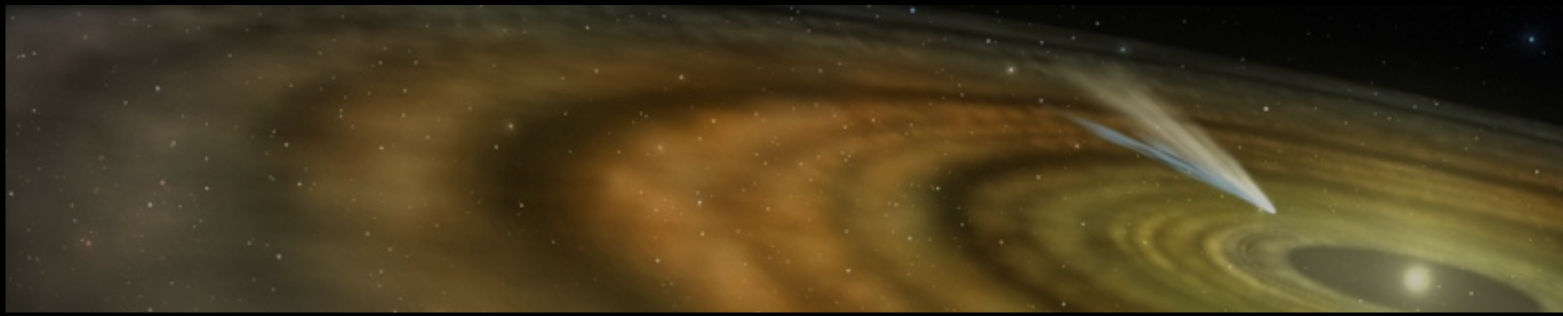
Planet’s source of emission?

Let us consider first reflected light

Assuming an albedo (reflectivity) ~ 1:

$$\frac{L_p}{L_\star} = \frac{R_p^2}{4a^2}$$

Reflected light is very faint: arguably very difficult or even impossible with current technology



Planets around other stars: the exoplanets

Some historical perspective:

- Planetary object confirmed around Fomalhaut
- Star is very bright, needed coronography
- Same proper motion as the star
- 10^{-7} brightness of the Sun
- 100 x brighter than reflection alone
- Planet is young: gravitational contraction still the source of energy (~ 100 - 300 Myr old)

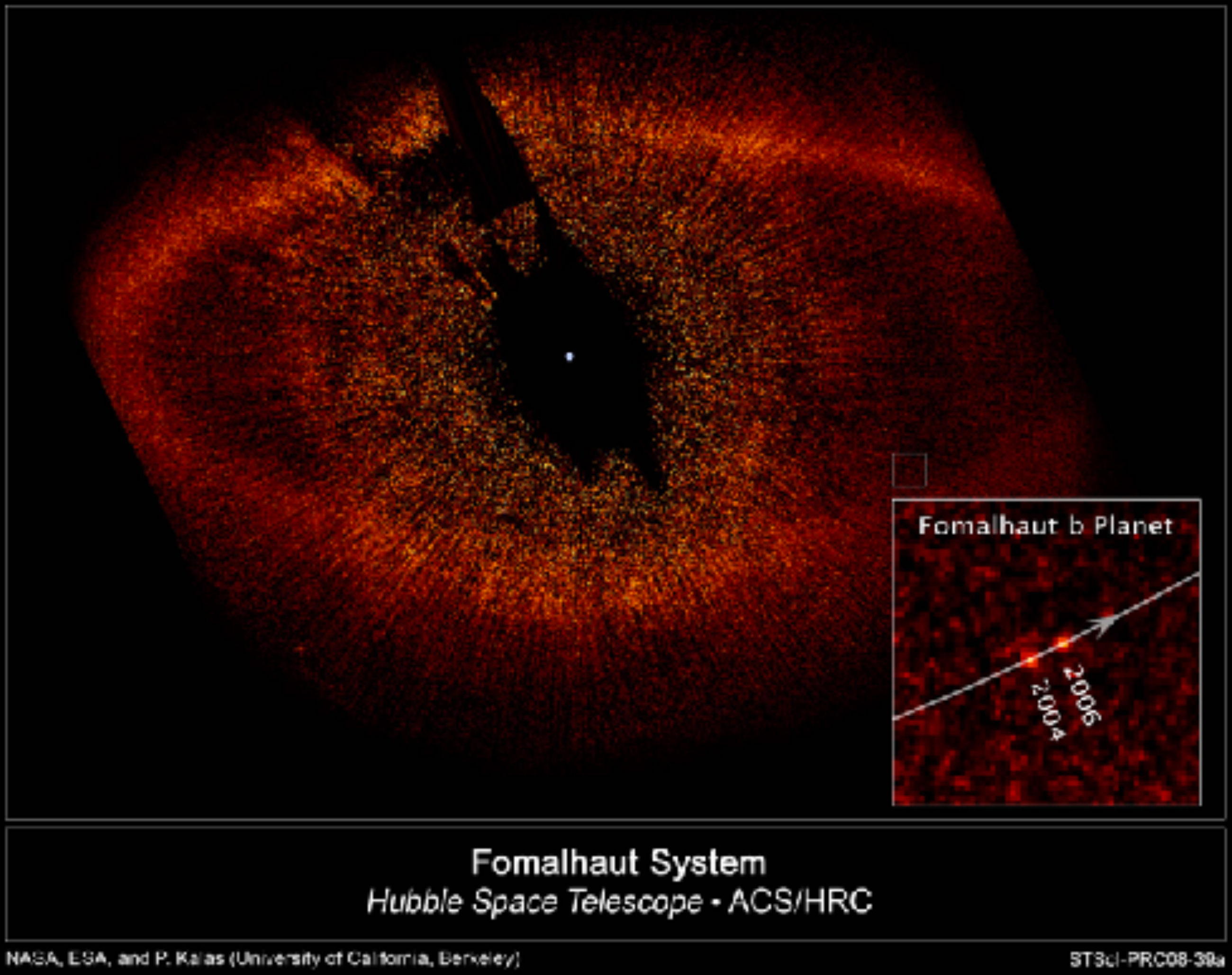
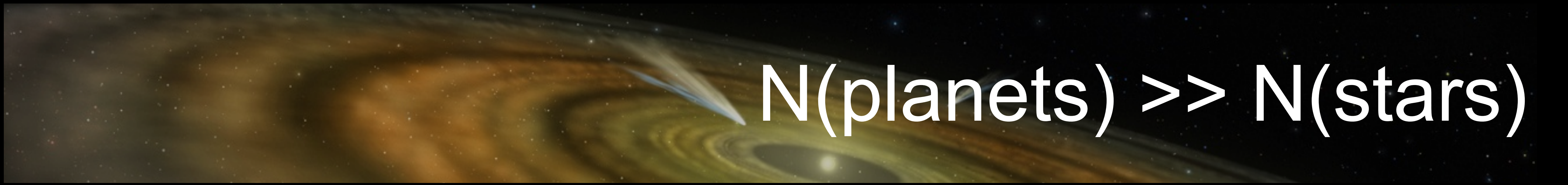


Image: Kalas et al. 2008, Science, 322, 1345

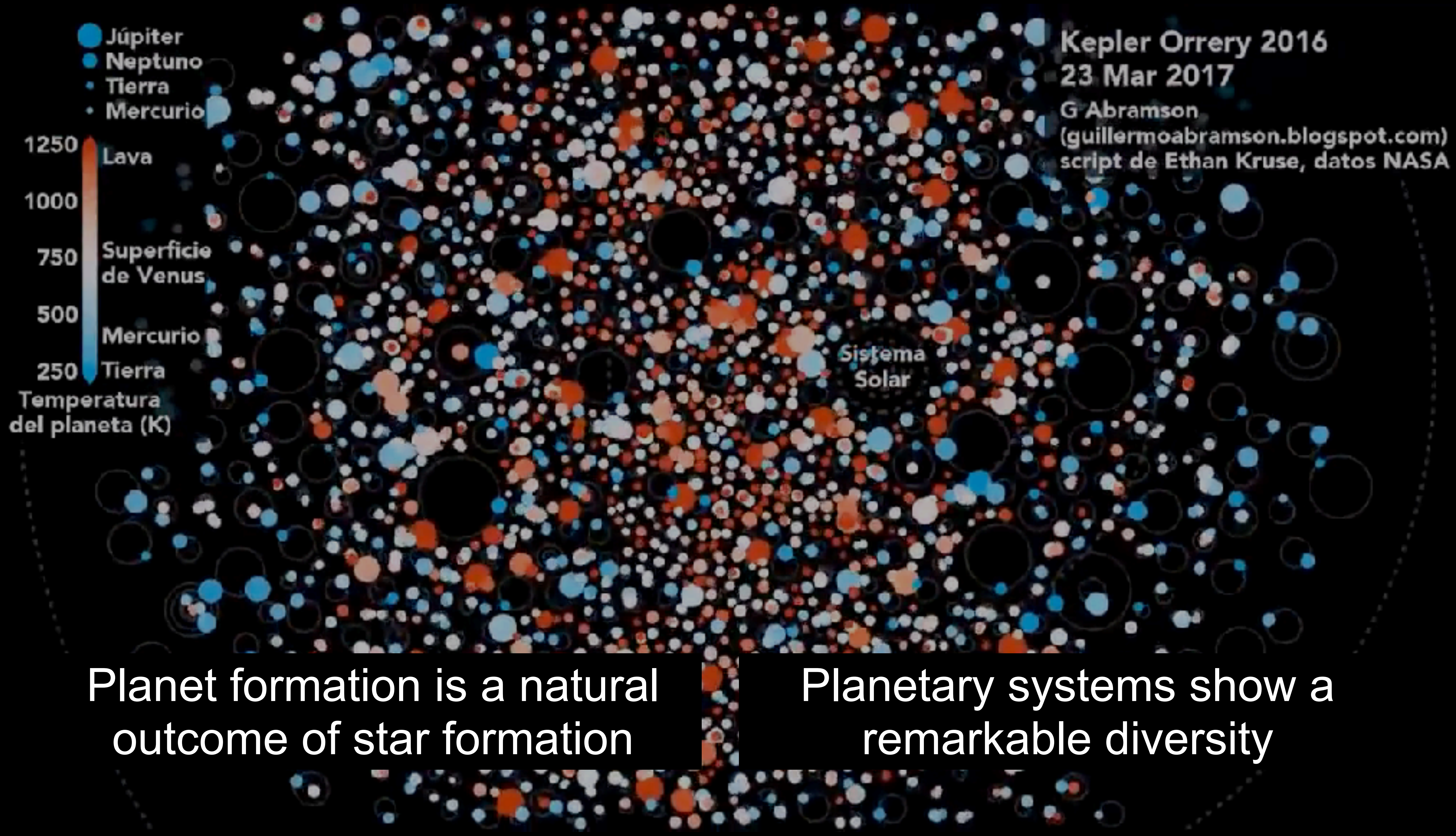
Detecting exoplanets: the radial velocity method

Video: NASA/JPL-Caltech

Detecting exoplanets: the transit method



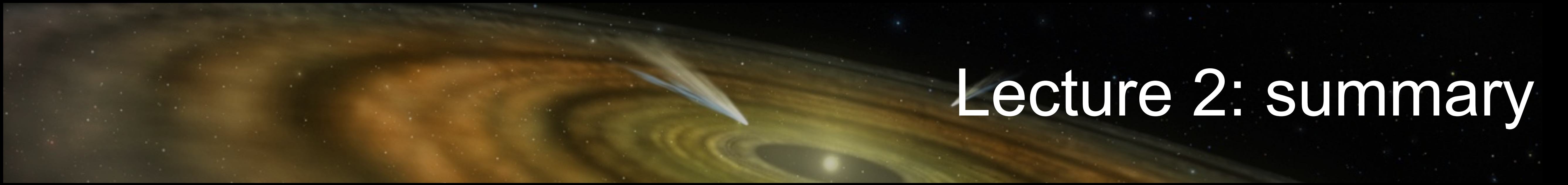
N(planets) >> N(stars)



Planet formation is a natural outcome of star formation

Planetary systems show a remarkable diversity

Movie: NASA/ G. Abramson, E. Kruse



Lecture 2: summary

In this lecture we discussed the following aspects of planet formation:

- Disks form around young stars as a consequence of angular momentum conservation during collapse

- Disks aid accretion of mass onto the new stars: young stars are bright in excess UV and X-ray emission

- Disks around young stars can be imaged in thermal dust emission (mm and cm wavelengths), in scattered light (optical and near-IR wavelengths) and in molecular lines

- Disks are the sites of planet formation: planet formation starts with the coagulation of small (micron-sized) dust grains, but the physics of growth to ~ km sizes remains poorly understood

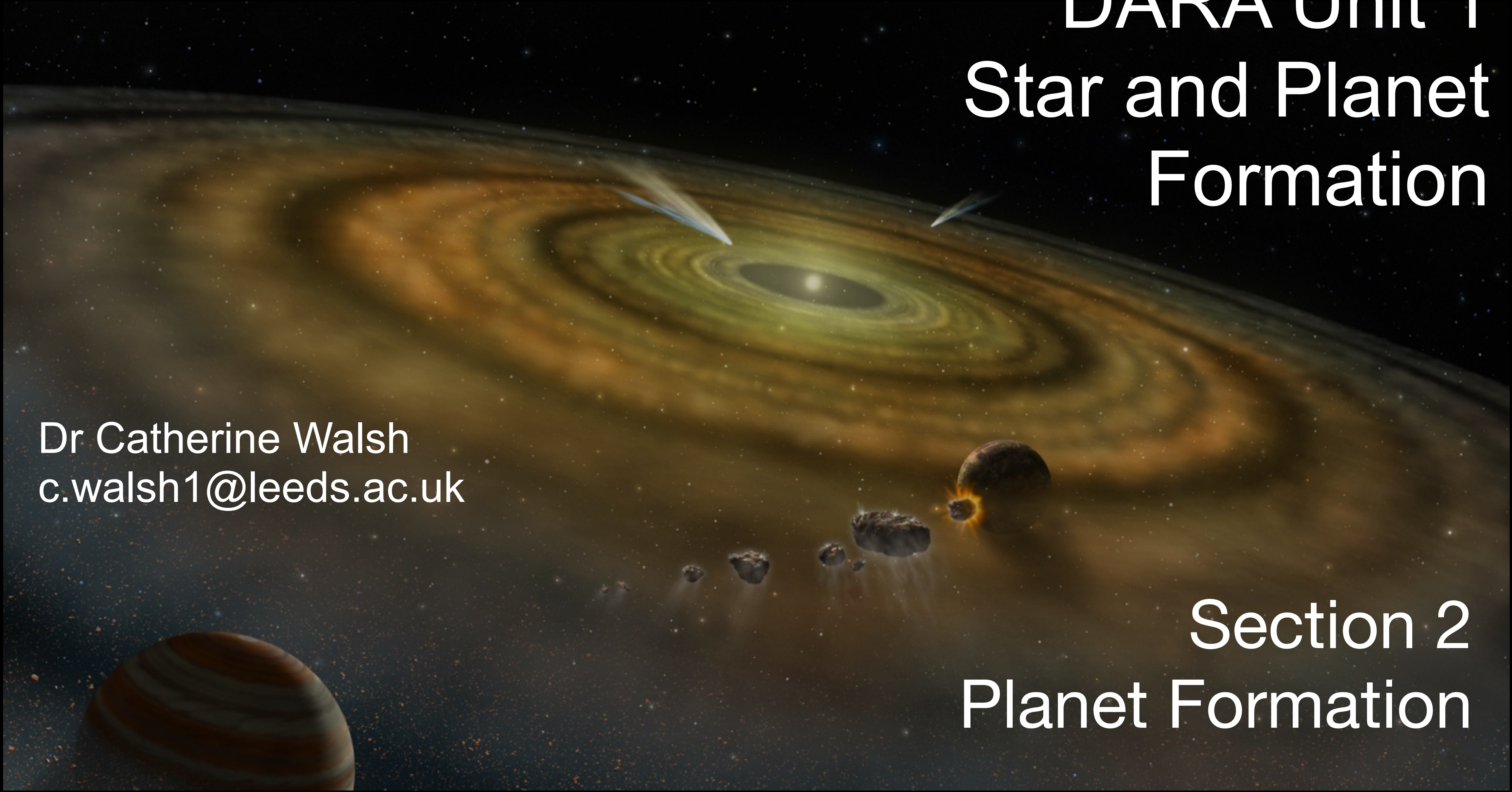
- There are thought to be two main modes of gas-giant planet formation: core accretion and gravitational instability

- The snowline (beyond which water ice forms) discriminates between the zones of rocky planet formation (rock and gas only) and gas- and ice-giant planet formation (rock, gas, and ice)

- The minimum-mass solar nebula describes the mass distribution of the disk within which the Solar System formed

- We can now detect planets around other stars: these planets are very different from those in the Solar System!

School of Physics and Astronomy
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES



DARA Unit 1
Star and Planet Formation

Dr Catherine Walsh
c.walsh1@leeds.ac.uk

Section 2
Planet Formation